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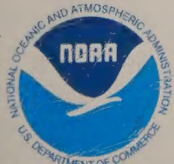
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Salmon, Oncorhynchus spp.

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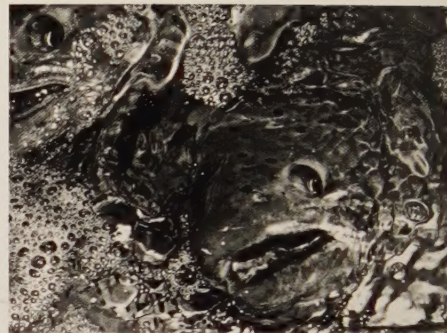


Marine Fisheries REVIEW

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Adult salmon at the Lower
Granite Dam adult trap, Snake
River, in 2010. Photo: Benjamin
Sandford, NOAA/NMFS/NWFS.



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The Distribution of Fishing Revenues Among North Pacific Regions and Communities

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Introduction

The U.S. North Pacific fisheries off the coast of Alaska generate approximately \$2 billion in ex-vessel revenues each year (NMFS, 2017). This income has been reported publicly for decades by federal and state annual reports (Fissel et al., 2015), but typically in a manner that attributes revenues to particular species, gear types, or broad areas within the North Pacific (e.g., Bering Sea, Gulf of Alaska). This study uses data on vessel ownership and residency to link the earnings from these fisheries to the individual cities and states in which harvesters live and likely spend their fishing returns.

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We also provide a detailed accounting of where the earnings from federally managed fisheries off Alaska flow. It provides a new and unique perspective on which fishing fleets generate the greatest revenues, describes the geographic location of vessel and quota owners in these fisheries, and analyzes various dimensions along which the distribution of fisheries revenues may have changed over the past decade in response to new management initiatives. We examine trends in fishery diversification within regions and across population size groups for fishing communities.

Since passage of the Magnuson-Stevens Fishery Management and Conservation Act in 1976, the North Pacific Fishery Management Council (Council) has actively managed most of the fisheries occurring in federal waters off the coast of Alaska, in conjunction with the U.S. Department of Commerce. North Pacific fisheries have a strong record of sustainable management and were among the first U.S. fisheries to adopt management programs that utilized individual fishing quotas and cooperatives (hereafter “catch shares”) with an objective to end the race for fish, and achieve economic and social goals (NPFMC,

2016b). The specific management approaches and objectives within these programs vary by fishery, a result of a complex public management process rather than a singular, unified strategic plan. That said, the general structure of many fisheries has gradually been tightened to “enclose” the fisheries and provide a more stable set of participants and quota allocations to specific groups (Holland, 2000). Often this begins with the implementation of limited entry rules which eliminate the creation of new permits or make it difficult for entry into a fishery.

License limitation programs follow, which further define the set of eligible vessels or individuals who may participate and, more specifically, define the nature of their eligibility. This degree of partitioning allows managers to then define catch histories, a set of eligible entities, and quota allocations which form the basis of a catch share program. In addition to improving economic efficiency and promoting sustainable harvest, socioeconomic objectives were often explicitly incorporated into the catch share programs.

Many of these programs in the North Pacific strive to strike a balance between increasing the economic success of incumbent harvesters and proces-

ABSTRACT—Our study uses data on vessel ownership and residency to link the earnings from North Pacific fisheries to the individual communities, cities, and states in which harvesters live and likely spend much of their fishing returns. We provide perspective on which fishing fleets generate the greatest revenues, describe the geographic location of vessel and quota owners in these fisheries, and analyze changes in the distribution of fisheries revenues over the past decade in re-

sponse to new management initiatives. We examine trends in fishery diversification for fishing communities within regions and across population size. Our results suggest greater complexity than some of the literature and stakeholder sentiment which argue that limited access and catch share programs cause small fishing-dependent communities to lose revenue. Using data from 2004 to 2013, we find no consistent trend of revenue or transfer of vessels from rural Alaska to Seattle, nor revenue con-

solidation away from smaller towns toward larger cities. We find that some regions are increasingly concentrated and reliant on the revenue generating capacity of a smaller vessel fleet. This trend is likely a result of consolidation in the number of harvesting operations. We also discuss the set of factors specific to management programs in the North Pacific that may have limited spatio-temporal revenue redistribution across community size or region following rationalization.

sors (whose capital is predominantly located in Seattle), while assuring adequate support for Alaska communities historically involved in commercial or subsistence fisheries. As a result, major North Pacific fisheries present the opportunity to observe the impact of catch share programs on aggregate performance and distributional outcomes in the short and medium term.

Various narratives have emerged regarding the consequences of enclosure policies and subsequent privatization of a public resource through catch share programs (Costello et al., 2008; Thebaud et al., 2012; Scheld and Anderson, 2014; Holland et al., 2017). These policies grant valuable secure access privileges to incumbent harvesters, which then present incentives to reduce costs and improve product forms, increasing efficiency and profitability. In doing so, however, they may also present a financial barrier for younger fishermen looking to advance their careers through ownership; the more successful the program at generating profits, the larger the purchase price for quotas and thus, difficulty entering the fishery (van Putten and Gardner, 2010).

Catch shares may also facilitate consolidation, lowering the aggregate costs of harvesting the annual quota, and in turn increasing economic efficiency (e.g., Bering Sea crab rationalization (NPFMC, 2016a)). However, such consolidation may displace crew jobs or change the nature of the remaining jobs to one in which they buy quota from quota owners and harvest it on others' behalf (Abbott et al., 2010). This study does not focus broadly on the general effects of catch share programs; instead, we examine ways in which the geographic participation and earnings of historically engaged regions may have changed after the new regimes were instituted.

Specifically, we use annual vessel-level data on federal fishery participants from 2004 to 2013 to describe shifts in the earnings from Alaska's fisheries, with a focus on the regional distribution of fisheries revenues, as represented by the owner address

of federal vessel licenses. During this period, we observe the medium-term effects of several large fisheries that implemented catch share systems in the mid- and late 1990's (halibut, *Hippoglossus hippoglossus*; sablefish, *Anoplopoma fimbria*; and walleye pollock, *Gadus chalcogrammus*).

We are unable to observe the initial impact of the catch share programs for halibut, sablefish, and pollock or the limited entry permit system established for Pacific salmon, *Oncorhynchus* spp., in 1975, so if consolidation of ownership occurred rapidly and then stabilized in these fisheries this will not be reflected in our data. We also see the short-term effects of fisheries that implemented catch share systems soon after the beginning of our data series. These fisheries include the crab fisheries (which target red king crab, *Paralithodes camtschaticus*; blue king crab, *Paralithodes platypus*; golden king crab, *Lithodes aequispinus*; opilio crab, *Chionoecetes opilio*; and Tanner crab, *Chionoecetes bairdi*), the rockfish fishery (which catches mainly rougheye, *Sebastes aleutianus*; short-raker, *Sebastes borealis*; and thornyhead, *Sebastolobus alascanus*), the non-pollock trawl catcher-processor fleet (which targets mainly Pacific cod, *Gadus microcephalus*; yellowfin sole, *Limanda aspera*; flathead sole, *Hippoglossoides elassodon*; rock sole, *Lepidopsetta bilineata*; and Atka mackerel, *Pleurogrammus monopterygius*), and many other fisheries which remain in legacy management.

By looking at a range of fisheries under different management regimes, we can explore whether there appear to be systematic differences in the revenue distribution among different management regimes. We first examine the distribution of revenue by vessel owner region and then discuss trends in regional diversification and concentration. The following section continues this same focus, but does so by community size to see if smaller or larger populations tend to be more susceptible to change over time. We conclude with a summary and discussion of our findings.

Approaches for Examining Distributional Impacts in Alaska Fisheries

Characterizing the effects of enclosure policies on fisheries and fishing-dependent communities has been approached from multiple disciplines and at different scales. Here we will discuss some previous studies and their approaches, followed by a description of the insights we hope to glean and the specific questions we plan to address. Although where relevant we attempt to draw inferences regarding the spatial redistributional effects of catch share programs, our analysis should not be perceived as an attempt to evaluate the overall effects of these programs. Readers are advised to peruse the literature discussed below and beyond.

At the community level, Carothers (2008) uses ethnographic methods to illuminate the linkage between transferable access rights, in the form of limited-access salmon permits, and a reduction of fishing activity within Aleutian Island communities. She argues that consolidation in the processing industry, away from small communities and into regional hubs, has removed a common source of personal credit which increases residents' vulnerability.

Monetized fishing access rights thus become a primary source of emergency credit for rural harvesters who experience personal financial shocks. Although strongly place-identified, they are rarely able to repurchase the permit and resume fishing, with the concomitant reduction of local crewing and support jobs from their rural communities; the community-level benefits of these jobs are not fully internalized as part of the private decision to sell.

This dynamic is consistent with the state-wide pattern of smaller communities being more likely to divest of halibut Individual Fishing Quota (IFQ) in the years immediately following the 1995 inception of the program (Carothers et al., 2010). However, Sethi et al. (2014a) use a suite of eco-

nomic indicators to show that permit and quota sales are not leading to a broad-scale reduction in fishing revenue associated with small communities over the period 1980–2010. Integrating across fisheries, they find that despite the stability in overall revenue, there are fewer fishermen and they participate in fewer fisheries, a trend also observed across West Coast federal fisheries (Holland and Kasperski, 2016).

This consolidation may increase vulnerability to management and natural fluctuations, such as climate change (e.g., Himes-Cornell and Kasperski, 2016). There is evidence that reductions in community diversification increase volatility in fishing revenues, but also that community portfolios are largely predetermined by location and thus unable to be influenced by management shifts (Sethi et al., 2014b). Reduced community-level economic dependence on fisheries primarily reflects growth in other sectors or the introduction of catch share programs that decrease community diversification in exchange for the stabilization of revenue (Holland and Kasperski, 2016).

Gho et al. (2012) use Alaska state fisheries permits data (in contrast to our federal fishery focus here) to examine changes in the age and geographic distribution of permit holders. They differentiate geographic changes attributable to permit transfers among parties living in different areas as well as relocation of a given permit holder. They also categorize the nature of the transfers in terms of what fraction were transferred to family, friends, or other, as well as according to the type of area to which the permit is tied (e.g., rural local and urban non-local). They find an overall net decline of 2,203 permits when examining the distribution of Alaska rural local permits from 1975 to 2010. However, rates of change for individual permit types have varied considerably over the time series. They also find the average age of permit holders to have increased in aggregate, again with some exceptions in specific fisheries.

This study uses the fishing revenue component included in Sethi et al. (2014a, b) to characterize changes in the distribution of earnings from North Pacific fisheries in the context of each fishery's enclosure policies. Additionally, however, we track regional changes and expand the focus to all communities that benefit from North Pacific fisheries, including those outside Alaska. Further, we use vessel-level data to decompose the revenue by fishery, capturing not just aggregate shifts, but shifts between fisheries within each region.

We explore three leading narratives about how enclosure and rationalization are affecting the distribution of, and variation in, fisheries revenues. First, we examine whether revenue in key fisheries is shifting among regions. This analysis illustrates the extent to which the small community processes presented in Carothers (2008) are leading to a broad-scale shift in fishing activity out of coastal Alaska, or Alaska as a whole, toward other regions.

Second, we evaluate whether small communities, as a category, are receiving a decreasing share in fishery revenues. Finally, we examine how individual vessels are altering the extent of their participation in individual fisheries. In particular, we look at whether vessels are becoming more dependent on fewer fisheries, and thus more exposed to fluctuations in individual stocks or management plans (Kasperski and Holland, 2013).

Understanding whether and how revenue distributions evolve is important because managers or stakeholders may have preferences over the distribution of benefits within their jurisdiction. For example, some rationalization programs (such as the Pacific Halibut and Sablefish IFQ Program) have had explicit management goals of retaining a local owner/operator fleet. In our examination of aggregate revenue by region, fishery, and community size, we find considerable stability over the period 2004–13. We find little evidence of ongoing change for both the set of mature enclosure programs and the most recent rationalization

programs. However, this observed stability is likely the result of policy efforts to minimize such impacts, as the most prominent trends in the data are associated with Community Development Quota (CDQ) group activity preventing erosion of, and in some cases increasing, the extent and breadth of fishery participation in coastal Alaska communities.

North Pacific Fisheries Overview

Table 1 presents the 18 fleets of vessels on which we focus our analysis, including 16 fleets managed by the North Pacific Fishery Management Council (NPFMC, 2012), and 2 fleets managed by the State of Alaska. We have ordered the vessel groups according to average annual revenue over the period of 2004–13. Most vessels in these fleets participate in multiple fisheries throughout the year, and some participate in fisheries in other regions.¹ Since these fleets are overlapping, the data reported in Table 1 reflects statistics for all vessels that reported landings within the fishery and common overlapping fleets are shown in the final column.

Pollock, by far the largest fishery in the United States by landings (NMFS, 2017), has the largest total revenue, split among catcher vessel (inshore), catcher-processor, and mothership fleets that manage collective allocations through cooperatives (Felthoven, 2002). The crab fisheries, collectively, exhibit the second highest average federal fisheries revenue after pollock;

¹As such, the “fleet” designation for the vessels reflects either the catch share program in which they are included or the predominant catch portfolio and gear type exhibited by the vessels. The “management style” pertains to whether the fishery is managed using catch shares (with specific quantities or shares of the total allowable catch going to individuals or groups) or another mechanism such as limited entry (in which the universe of eligible participants is strictly defined, but the allocation of catch for each participant is not). Some catch share programs function with individual quota holders as the management unit, while others operate as cooperatives; however, cooperatives have even formed in some of the limited entry fisheries with a manageable number of vessels. More information on these fleets can be found in NPFMC (2012). More specificity about the nature of quota allocations and transferability of the catch share fisheries is included in Holland et al. (2015).

Table 1. – Characteristics of Alaska fleets by average annual value, 2004–13.

Fleet description	Avg. share of annual revenue to AK ¹	Avg. Value \$M (Std Dev)	2010 Landings (Mlbs)	2013 Active vessels	Management style, quota share (QS) allocation method for catch shares, (year implemented)	Current management actions or issues	Common Overlapping fisheries ²
BSAI Crab Catcher vessels and catcher-processors targeting various species of crab with pot gear in the Bering Sea	28.13	191.87 (\$3.80)	72.40	114 (282 in 2004 pre-IFQ)	Catch share; QS to individuals, can operate as co-op (2005)	ROFO Participation and voluntary lease rate caps	Pot, Salmon tendering
AFA Catcher Vessels BSAI pelagic trawl pollock delivered inshore	1.49	179.44 (27.22)	890.67	84	Catch share; QS to group, do operate as co-op (1999)	Chinook salmon bycatch	Central Gulf Trawl, Pacific Hake
Halibut IFQ Longline catcher vessels targeting halibut in GOA and BSAI	68.52	175.30 (35.04)	52.55	910 (max of 1471 in 2004)	Catch share; QS to individuals (1995)	Declining biological availability	Salmon, Sablefish
AFA Catcher-processor BSAI pelagic trawl pollock harvested and processed on board	7.82	143.59 (40.96)	313.73	16	Catch share; QS to group, do operate as co-op (1999)	Chinook salmon bycatch	Pacific Hake
State Salmon Landings of salmon by vessels also participating in at least one Federal fishery	93.11	125.43 (28.87)	225.19	683 (max of 814 in 2005)	Limited Entry (1973)	Volatility in landings and prices	Halibut IFQ
Amendment 80 BSAI trawl catcher-processors not targeting pollock. Mainly targeting flatfish and Pacific cod or rockfish and Alka mackerel.	0	114.02 (29.27)	162.86	19 (23 in 2004 pre-A80)	Catch share; QS to individuals, do operate as co-op (2008)	Halibut PSC reductions	Central Gulf Trawl
Sablefish Fixed gear catcher vessels and catcher-processors predominantly targeting sablefish	50.9	83.76 (16.70)	25.11	354 (max of 426 in 2004)	Catch share; QS to individuals (1995)	Addition of pots, seabird takes	Halibut IFQ, Salmon
Catcher-processor Hook and Line Freezer longliners targeting BSAI and GOA Pacific cod	21.7	56.75 (16.63)	231.76	35	Limited Entry; operate as co-op (2006)	Halibut PSC and seabird takes	Sablefish
Central Gulf of Alaska Trawl Catcher vessels and catcher-processors primarily targeting flatfish, pollock, Pacific cod, and rockfish	33.41	37.62 (11.05)	218.80	66	Limited Entry (2000) except catch share. Central GOA Rockfish (2007)	Halibut PSC reductions, rockfish quota program	AFA Catcher Vessels
AFA Mothership BSAI trawl pollock delivered to mothership and processed on board	7.04	37.47 (4.37)	155.01	14	Catch share; QS to individuals, do operate as co-op (1998)	Chinook salmon bycatch	AFA Catcher Vessels, Pacific Hake
Groundfish Pot Catcher vessels and catcher-processors using pot gear primarily to target BSAI/GOA Pacific cod	50.33	27.46 (8.20)	131.10	126 (max of 149 in 2007)	Limited Entry (2000) - in 2009 gear-specific co-ops established	Halibut and crab quota	Halibut IFQ, Crab, Salmon
Western Gulf of Alaska Trawl Catcher vessels and catcher-processors primarily targeting flatfish, Pacific cod, pollock, and rockfish	33.59	11.92 (2.87)	91.52	40	Limited Entry (2000)	Halibut PSC reductions	Salmon, Central Gulf Trawl, Halibut IFQ, A80
Non-AFA BSAI Trawl Catcher vessels primarily targeting Pacific cod with bottom trawls	4.1	10.26 (5.94)	43.87	14	Limited Entry (2000)	Halibut PSC reductions	Central Gulf Trawl, Western Gulf Trawl
Catcher Vessel Hook and Line Groundfish longline catcher vessels predominantly targeting Pacific cod	89.35	6.57 (2.02)	19.05	66 (max of 96 in 2008)	Limited Entry (2000)	Halibut PSC reductions	Salmon, Sablefish, Halibut IFQ
Scallop Catcher vessels targeting weathervane scallop using dredges	5.65	3.62 (0.94)	0.46	5	Limited Entry (1999) - in 2000 co-op established moratorium on permits (1997)	Ecosystem effects of dredging	Non-AFA BSAI Trawl, Crab
Halibut CDQ Catcher vessels actively fishing halibut quota owned by CDQ groups in Western Alaska	91.33	3.35 (3.76)	2.41	244 (zero until 2009)	CDQ (1995)	Declining halibut TAC, addition of Pacific cod CDQ	Salmon
Jig Catcher vessels using jig gear (actively fished vertical lines) and predominantly targeting BSAI/GOA Pacific cod	91.78	0.39 (0.24)	8.45	171 (max of 251 in 2012)	Limited Entry (2000); operate as co-op	Halibut quota	Halibut IFQ, Salmon

¹Average of 2004–13 annual percentage of fleet's total revenue attributed to vessels with CFEC owner addresses within Alaska.²Other fisheries where vessels from a given fleet are likely to participate.

their revenue share in Alaska has been trending upwards since the implementation of a catch share program in 2005 (NPFMC, 2016a).

The IFQ halibut fishery, rationalized with sablefish in 1995, has revenues comparable to the shoreside pollock fishery, although revenue has been declining along with decreasing stock levels exhibited over the last decade. Despite the high degree of natural fluctuation in individual river systems, the large limited-entry state salmon fishery contributes significantly to the fishing portfolios of communities throughout Alaska; note however that, as stated earlier, our study considers only the salmon caught by vessels that also fish in federal fisheries (as salmon is managed by the state and those vessels which just fish in state fisheries are not included here).

Revenue from the Amendment 80 groundfish trawl fleet has steadily increased since cooperative-based rationalization in 2008. The IFQ sablefish fishery is a medium-sized fishery with stable revenues. In comparison, the remaining fisheries such as scallop, Central Gulf trawl, and groundfish pot or longline are all relatively small in total revenue; however, many fisheries play significant roles in their regions' economies.

One component of fisheries management in Alaska worth noting is the annual set aside of CDQ for several groundfish and crab species harvested in Alaska. The CDQ corporations were first established by the NPFMC in 1992 and then made permanent under reauthorization of the Magnuson-Stevens Act in 1996 in order to represent the fishing interests of western Alaska's regional coastal communities. Six regional CDQ groups in western Alaska receive allocations for a portion of the total allowable catch (TAC) for groundfish, crab, halibut, sablefish, and prohibited species (PSC).

Typically, around 10% of the TAC is set aside. In some areas, however, up to 100% of the TAC is set aside for CDQ halibut, and up to 20% for fixed-gear CDQ sablefish. The 2017 allocations can be viewed at <https://alaskafisher->

[ies.noaa.gov/sites/default/files/reports/annualmatrix2017.pdf](https://alaskafisheries.noaa.gov/sites/default/files/reports/annualmatrix2017.pdf). Aside from the higher proportion of the halibut and sablefish TACs set aside for CDQ, the nature of these fisheries differs markedly from the way CDQ allocations are fished in more industrialized fleets made up of larger vessels based out of Seattle (Szymkowiak and Himes-Cornell, 2018).

In the crab and groundfish fleets, CDQ is primarily leased by these vessels and fished alongside their non-CDQ allocation. Alternatively, in the halibut (and sablefish) fisheries, the CDQ is more likely to be fished by vessels owned by the residents of CDQ regions who do not have meaningful participation in any other federal fleet. Several CDQ groups have been successful in leveraging their allocations into ownership shares in crab and groundfish vessels, with those CDQ landings occurring alongside non-CDQ landings and within overlapping fleets (American Fisheries Act and Amendment 80). For purposes of this study, we examined only one specific CDQ halibut fleet but note the significance of CDQ for various fleets and regions when relevant.

In most fisheries we examined, real revenue has been increasing, reflecting management that sets catch at sustainable levels, and improved handling and higher-valued product forms facilitated in many cases by eliminating the race for fish. However, pollock experienced a downturn in 2009–10, mostly attributable to small year classes among the 3- to 8-yr-olds typically targeted. Revenue has not yet returned to abundant 2008 levels. Salmon product forms have improved to maintain recent average price levels among increasing competition from aquaculture (Knapp et al., 2013). Revenue from halibut has dramatically fallen as the stock, which is managed under treaty by the International Pacific Halibut Commission (IPHC), has seen biomass and size-at-age decline since 2004 (for reasons not fully understood and not necessarily associated with the fishery), leading to a 63% reduction in

IFQ halibut quotas between 2004 and 2013 (NMFS/AKRO, 2016b).

Importantly, most of these revenue gains are from market improvements, as most North Pacific fish stocks have been healthy and relatively stable throughout this period. Thus, total harvest has not increased. In the Bering Sea/Aleutian Islands, total harvest has been constrained throughout this period by a longstanding “ecosystem cap” of 2 million t (Witherell et al., 2000). Although the sum of species-specific Allowable Biological Catches (ABC) has been in the 3–3.5 million t range, the Council issues TACs totaling only 2 million t each year, to introduce a buffer so most TACs do not fluctuate with natural variation in their stocks. A similar cap of 800,000 t exists for the Gulf of Alaska, though total ABCs have stabilized just below it.

Fishery Revenue Data

The confidential data used in our analysis was provided by the Alaska Fisheries Information Network (AKFIN), an interagency organization that maintains fisheries data derived from NMFS and the State of Alaska sources (including the electronic fish tickets). When fish or shellfish are caught and sold to the first buyer, the buyer enters information into the state of Alaska's eLandings database and generates an electronic “fish ticket.” These tickets reflect the landing vessel, species, quantity, and ex-vessel prices for shoreside fisheries, allowing computation of ex-vessel revenue estimates for each delivery. Catcher-processor data reports the value of all products produced from the raw fish and thus reflect value added from primary processing. To generate consistent estimates of ex-vessel value across both catcher vessel and catch-processor fleets, NMFS utilizes a two-step procedure in order to impute the ex-vessel value of the fish used to create the catcher-processor products (Fissel et al., 2015).

To create the distinct fleets discussed in this manuscript, AKFIN staff analyzed each vessel's landing patterns and permit holdings to determine the

fishery in which it was participating at the time fish were landed. It can be difficult to associate landings within a fishery because the same species can be landed either through directed targeting under one management plan or as bycatch when the same vessel is targeting other species. For example, some Amendment 80 groundfish fleet vessels can participate in directed fishing for Pacific cod, but also they can land a “maximum retainable amount” of Pacific cod as a percentage of flatfish (*Pleuronectiformes*) when targeting flatfish. In addition to these interlinked federal fisheries, we consider these vessels’ landings in the state-managed salmon and “other state” fisheries within 3 n.mi. of shore. AKFIN does not have data on participation in fisheries outside the Alaska management regions (e.g., American Fisheries Act (AFA) pollock vessels also catch Pacific whiting, *Merluccius productus*, off Oregon and Washington), or information on non-fishing revenue (such as tendering in various salmon fisheries), so we focus exclusively on participation in the fisheries off Alaska. Our dataset was limited to 2004–13 because the process of associating landings within fleets could only be completed reliably for these years of data when this research was undertaken.

We use the total annual revenue each vessel derives from each fishery in which it participates to assess temporal changes in the regional and community-scale distribution of fishing revenues. We focus on revenue because it is available for all fishing fleets, but we recognize that there are limitations to this variable, such as changes in costs or added value. Costs may vary significantly on a decadal scale as people and capital move among regions and fisheries and efficiency-enhancing rationalization programs are introduced; therefore, we are unable to conduct a formal welfare analysis that would instead calculate net benefits of the harvest sector. Additionally, ex-vessel revenue does not capture value added through processing, which can be significant depend-

ing on the product form. However, examining changes in processing plant volume and locations is beyond the scope of the current study.

To associate a vessel’s revenue with a region, we use the “vessel owner city” field maintained by the Commercial Fisheries Entry Commission (CFEC) when vessel owners file for their vessel license each year.² This variable is primary, and prevalent, in that it was missing for only 38 of the 18,370 total observations. The vessel owner’s city is not necessarily reflective of where the majority of fish is landed, or where the vessel spends the majority of its time; however, it is suggestive of where the owner—who collects the largest share of fishing income—spends income, and may also reflect where the vessel purchases some supplies and hires crew. We recognize this proxy may not be representative of where all the crew factor payments flow, but it is the best indicator at our disposal.

An additional concern is that attributing revenue to vessel owners may inflate the actual benefits accruing to the vessel owner’s community when the vessel owner is not the same as the quota or permit owner, as may be the case when emergency transfers, hired masters, or outright leasing provisions are common. Approximately 40% of vessels in the halibut fleet and 55% of vessels in the sablefish fleet reported using hired masters, and many use emergency medical transfers to bypass owner-on-board requirements (NPFMC, 2016b). Anecdotally, in the halibut and sablefish fisheries lease rates range from 50% to 60% of gross revenue (NPFMC, 2016b) and empirically, lease rates range from 30% to 65% of gross revenue in the

²AKFIN provides an alternative, vessel hauling port, which is a landings-based estimate of the vessel’s home port. This variable had 3,059 missing vessel years (almost entirely non-federal vessels), and after conducting our analysis with both variables we did not observe a statistically different distribution of aggregate revenues across regions. For this reason, as well as brevity and greater data availability, we have restricted our discussion to results based upon vessel owner city, with additional figures based upon hauling port residing in our appendix.

crab fishery (NPFMC, 2016a) which means considerable revenue accrues to quota owners, rather than vessel owners. Despite the large share of ex-vessel revenue that accrues to the quota owner, the proportion of vessels that lease quota is relatively stable over the course of our study (NPFMC 2016a, b) which means changes in leasing prevalence are not driving our results.

The relationship between the registered vessel owner’s city and local benefits may also be weaker for corporate-owned vessels, typical of industrial fleets, where the profits from the corporation are distributed among many individuals in different localities. Neither NOAA nor CFEC maintain data on individual ownership of corporate entities, prohibiting disaggregation of these revenues. An important exception is when vessels are owned by regional CDQ groups. The CDQ groups use revenue from fishing or leasing the quota to reinvest in community fishing involvement, as well as the education and welfare of their community members. Because CDQ groups disclose their vessel ownership interest in their annual reports, we are able to associate those vessels’ revenues with the CDQ regions.

Regional Revenue Distribution

The second column of Table 1 lists the percentage of fishery revenue earned by vessel owners residing in Alaska; this varies widely by fishery. Four of the largest fisheries were never operated out of Alaska. The AFA catcher vessel, catcher-processor, and mothership pollock fleets, the Amendment 80 non-pollock groundfish fleet, and the cod freezer-longliners were almost entirely developed with Washington State capital—or foreign capital that moved to Washington following the American Fisheries Act. In contrast, Gulf of Alaska groundfishing, jigging, and state fisheries—especially salmon—are strongly rooted to Alaska ownership, and have been historically pursued by residents of small and medium-sized Alaska communities.

In between, crab, halibut, and inshore pollock have significant own-

ership interests inside and outside Alaska. These different geographies of ownership can lead to conflicts among fleets when they catch the same species. For example, significant management effort focuses on balancing the distribution of Chinook salmon between the Alaska directed salmon fisheries and bycatch by the predominantly Washington pollock fleet (NMFS/AKRO, 2016a). A similar tension exists between halibut caught by the Alaska IFQ/CDQ fleet and halibut caught incidentally by the primarily Washington-based Amendment 80 fleet in their pursuit of groundfish (NMFS/AKRO, 2016a).

To analyze movement of fishing revenues, we identify a set of regions with significant representation in the North Pacific Fisheries. In Western Alaska, we use CDQ Program region boundaries to define the regions: we pool Coastal Villages and Yukon Delta regions as AK Central West due to the very small number of observations. The AK Aleutians and Pribilof region pools the revenue from Saint Paul Island's Central Bering Sea Fishermen's Association (CBSFA) with communities located within the boundaries of the Aleutian Pribilof Island Community Development Association (APICDA). We also include Kodiak, Anchorage/Matsu, Cook Inlet/Prince William Sound, and Southeast as distinct regions, along with Other Alaska. Outside of Alaska, we distinguish the Seattle Metropolitan Statistical Area (MSA), Other Washington, Oregon, California, and Other States.

Figure 1 shows the distribution of revenue from individual fleets, by residence of the harvesting vessel owner. Within each region, the left pie chart shows the average revenue contribution from each fishery in 2004 through 2006, and the right pie reflects revenues from 2011 through 2013; the areas of the pie are proportional to the region's share of total North Pacific fishery revenue during each time period.

Seattle MSA is dominant in all years, whereas some regions, such as Alaska Other and those in western

Alaska, have such a small share of revenue that the inset shows the individual fisheries. Between the two time periods, real revenues in all regions grew an average of 7%. Some regions grew more than others, including Seattle MSA, Anchorage/Matsu, and Norton Sound. Total revenue fell in regions such as Southeast, Bristol Bay Lakes/Peninsula, and Other Washington.

Looking within regions across time, the shoreside and catcher-processor pollock fleets dominate Seattle MSA revenue, and their regional revenue share remained stable. Increasing revenues from the Amendment 80 groundfish fleet increased its share of income associated with Seattle, as well as other U.S. regions outside the Pacific Northwest. Owners from both Oregon and Kodiak, Alaska, are increasingly involved in the Central Gulf trawl fleet and rationalized crab, while reducing their dependence on halibut IFQ revenue. Share of revenue from halibut IFQ reduced across almost all regions, and halibut CDQ revenue is not a large source of revenue for any region except AK Central West and AK Aleutians. Salmon revenue is an important contributor to owners residing in the Aleutians, Bristol Bay, Cook Inlet, Kodiak, and Southeast, and these regions' reliance on salmon is trending upwards. Crab harvest patterns changed most significantly in Norton Sound, Kodiak, and Anchorage/Matsu, where investment in the fishery increased.

Total Regional Revenue

To clearly identify intertemporal trends in the regional distribution of revenue, Figure 2 shows the percentages of total ex-vessel revenue from all fisheries according to the region of the vessel owner's city. Although the proportion of revenue for vessels owned outside of Alaska is large (approximately 60%), allocation of revenue across regions appears to be largely stable. There is no clear trend of residents from outside of Alaska gaining share following the rationalization of the crab fleet in 2005 or the Amendment 80 fleet in 2008. In recent years, the larger share of revenue is captured

by vessel owners located outside of Alaska; however this is a reversion to levels from the early years of the data. More populous regions like Anchorage and Seattle MSA gained shares, while southeast Alaska and other parts of Washington lost shares. The share of the most rural areas surrounding the Gulf of Alaska and the Bering Sea is stable.

Regional Fishery Dependence

While the revenue shares of each region may be stable, enclosure and rationalization policies may shift the composition of the fisheries that contribute to each region's revenue. Equivalent revenue levels from different fisheries could imply different levels of profitability and net benefits if the cost profiles differ considerably among fisheries, or, if the number of fisheries in which a region participates has dropped substantially, substitution possibilities to healthier and more abundant fisheries may be diminished. To investigate the possibility of such compositional changes, we calculate several Herfindahl-Hirschman Indexes (HHI) (Herfindahl, 1955; Hirschman, 1964). The HHI is a standard measure of concentration that takes on a value between 0 and 10,000 and is equal to the sum of squared market shares across entities in an industry. As such, it is very sensitive to movement away from complete concentration and relatively insensitive to changes in diverse industries. Kasperski and Holland (2013) used HHIs to examine how the diversity of fisheries in which a vessel participates relates to its year-over-year variation in profits, finding that it is riskier to be less diversified across fisheries; we explore these business-level effects below.

To assess whether some regions are becoming more dependent on individual fleets, Figure 3 shows the log-HHI of each region's revenues across the distinct fleets studied.³ This is calculated for each region by

³We report natural log HHIs, with a maximum of 9.21, to show changes in fisheries with numerous smaller vessels fisheries alongside industrial fisheries with fewer vessels.

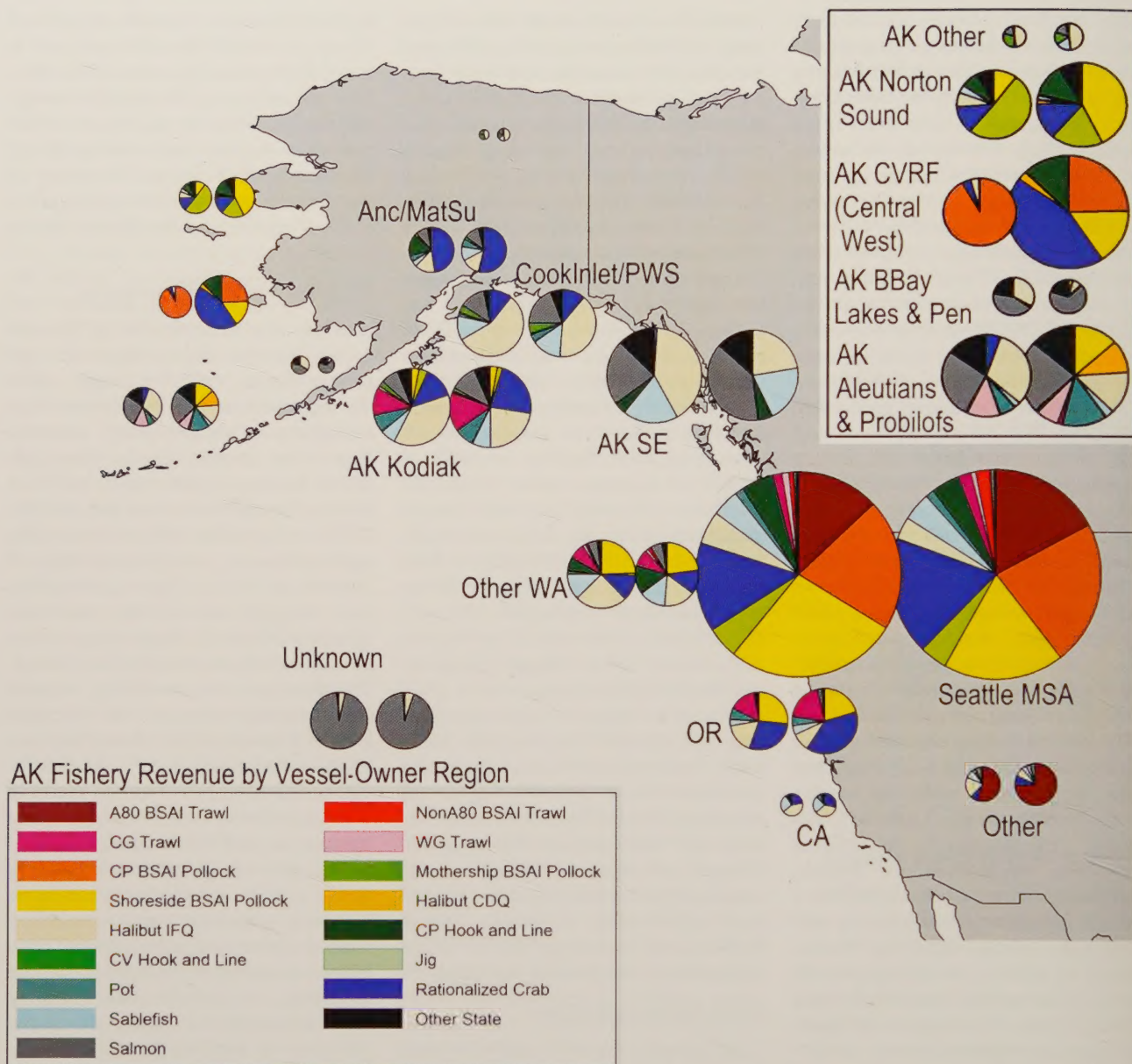


Figure 1.—Regional distribution of revenue by fishery in 2004–2006 (left pie in each region) and 2011–2013 (right pie in each region). Pie area is proportional to share of total revenue from all fisheries.

determining the region's total revenue from each fleet listed in Table 1, determining the share of the region's total fishery revenue associated with each fleet, and using that share as the basis for the HHI. Most regions do not show a strong trend, indicating they are as diversified across fleets as they were 10 years ago. This finding indicates there is not strong evidence

that regions are forced into fewer or lower-valued fleets.

The high HHIs for AK Central West reflect a single CDQ group-owned pollock catcher-processor that accounts for more than 90% of revenue in some years. The increasing HHI for Bristol Bay reflects that it is increasingly concentrated within certain fleets. Kodiak has become less concentrated, as

it was highly dependent on halibut and crab through the early 2000's but has diversified (while preserving revenue share in the crab fishery overall) by increasing its portfolio of jig and pot landings.

The regional level stability does obscure some shifts within individual fleets. In the newly rationalized crab fleet, the revenue shares of Anchor-

age, Kodiak, and Norton Sound grow, while residents of southeast Alaska and the Aleutians no longer participate, and Washington's role is shrinking. Residents of southeast Alaska appear to be transitioning into the state's salmon fishery, as their share of salmon revenue is on the rise since the implementation of the crab quota system. Communities in the Aleutians increased their participation in the Central Gulf trawl fishery following the crab rationalization.

Within the fleets with CDQ allocations, there is a relatively large degree of variation in the vessels fishing CDQ allocation. For example, over the course of the CDQ halibut program, there has been a trend of increased revenue going to local harvesters in the Central Western and Aleutian regions in particular. Conversely, almost all vessels landing CDQ crab and groundfish quota were initially owned outside Alaska but there has been a strong trend of CDQ groups buying shares in vessels, especially those in close proximity to the fishery (see Supplemental Figure O for halibut CDQ fleet plots).

Number of Vessels Participating

Changes in fishery management can influence the number of vessels participating in a region, independent of the fisheries from which revenue is drawn. Figure 4 shows the number of fishing vessels in each region. The most numerous region, southeast Alaska, is losing vessels, corresponding with its drop in revenue share. Most other regions are experiencing a slight downward trend in the number of vessels, consistent with theories predicting an aggregate harvesting cost reduction through consolidation of harvesting operations over time after the introduction of catch shares. Some small and remote regions of rural Alaska, such as Norton Sound and Alaska Central West, are gaining vessels, where CDQ groups buy up capital and expand their harvesting operations. Although there is a concurrent decline in vessels in the neighboring region of Bristol Bay and Peninsula, the vessel level data indicate that the vessels moving into

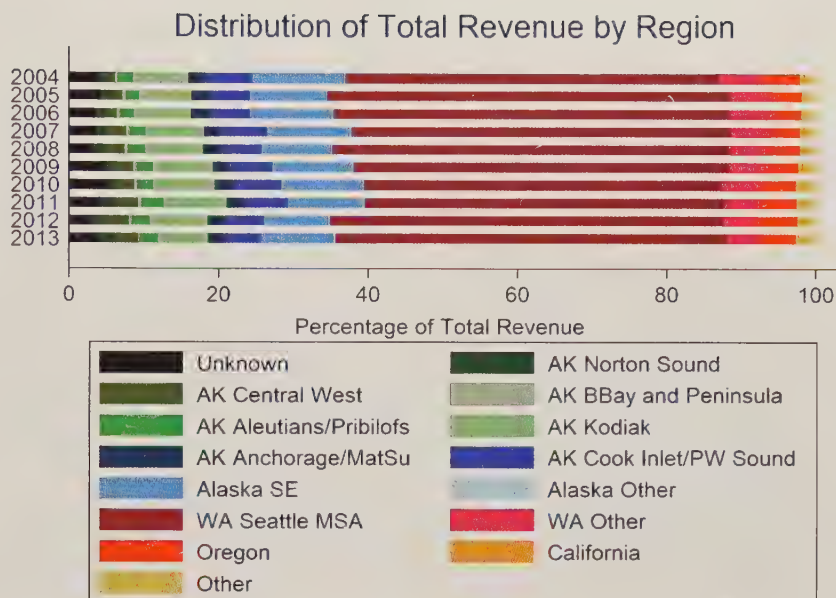


Figure 2.—Distribution of ex-vessel revenue by region.

Western Alaska and the CDQ regions are coming from outside; this may be attributable to frictions in labor and credit markets or existing capital being in poor condition.

A decline in vessels in one region could imply that revenue is leaving that region or that revenue is simply transferred to still-active vessels within the same region; these processes have different distributional implications outside the harvesting sector. Figure 5 shows the log-HHI of each region's vessel revenue, or how well diversified each region is across its vessels. This measure calculates total revenue for each vessel and determines each vessel's share of its region's total revenue, which is used as a basis for the HHI. Most regions have increased slightly in vessel revenue HHI, reflecting that most regions derive larger shares of their revenues from fewer vessels. Norton Sound is decreasing, partly reflecting the increase in the number of vessels seen above. AK Central West is decreasing, but excluding the single pollock catcher-processor, there is little trend.

While Figure 5 shows negligible trends in region-level HHIs, it may mask a concentration of revenue with-

in communities from each region. We calculate the HHI for every community to reflect how diversified it is across vessels. This measure calculates total revenue for each vessel and determines the vessel's share of its community's total revenue, which is then used as a basis for the HHI. Slightly less than half the communities have HHIs approaching 10,000, reflecting that they have only one fishing vessel (Supplemental Figure T).

Among the communities with more vessels, at the 25th percentile of HHI, concentration changes negligibly, from 3,360 in 2004 (corresponding to a 45/30/25/5 market share split, if there are four vessels), to 3,297 in 2013. This suggests that even at the individual community level, fishing communities are not becoming increasingly dependent on fewer and fewer vessels during the period of our data. This could still occur with a decreasing total number of vessels if the remaining smaller vessels are increasing their market share.

Population Size Analysis

Although Alaska regions have not seen a systematic decline in fishery revenue share or increasing reliance on

Regional Diversification Across Fisheries

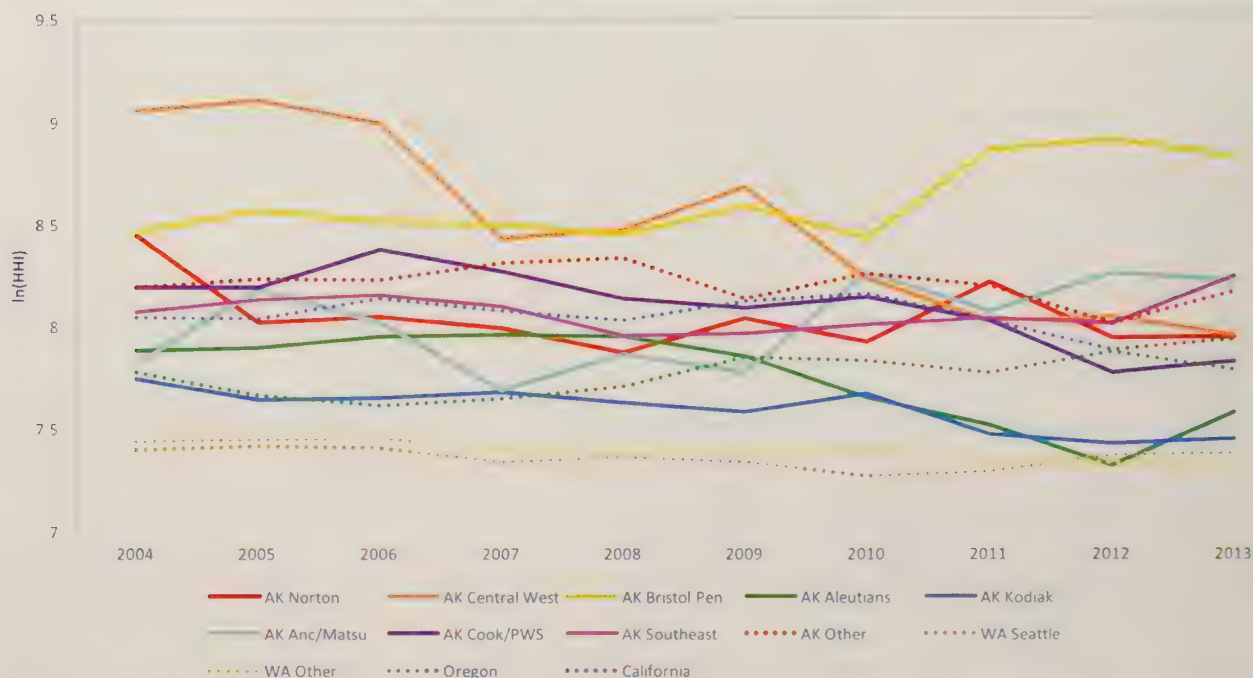


Figure 3.—Log-HHI of region's revenue across fisheries, indicating how each region's fishery revenues (to resident owners) are concentrated across fisheries.

certain fisheries over the last decade, revenue may nevertheless be transferring out of small communities into larger towns within the same region. To avoid obscuring any movement from the smallest (and perhaps most vulnerable) communities to larger municipalities, we used census data to determine the population of each vessel-owner city, and assigned it to one of six bins for analysis. For comparability within the literature, we used the bins that Carothers et al. (2010) identified for small remote fishing communities with under 7,500 residents.

Figure 6 shows the distribution of total ex-vessel revenue from all fisheries according to the population of the vessel owner's city. Although the proportion of revenue that goes to vessels owned in cities with more than 25,000 residents is large (approximately 60%), allocation of revenue across population bins is largely stable. From 2004 to 2008, large cities gained share from towns in the 2,500–7,500 bin. In

2009–10, when there was low revenue for pollock (majority of ownership in large cities), this trend reversed, but reemerged once pollock harvests increased again. All other population bins are relatively stable except for that of communities in the 1,500–2,500 bin, which has fallen from 3% of the total to 2%.

When large communities gain even small amounts of the total share, it does appear to be at the expense of a handful of smaller towns, mainly located in southeast Alaska. However, this is largely reflecting features idiosyncratic to the individual fisheries represented in these community types, and any systematic trend is swamped by natural variation in TACs and prices. In many cases, these shifts represent the decisions of single individuals. Importantly, there is not a dramatic trend of residents from large cities gaining share following the crab rationalization, and all Amendment 80 vessels were

owned by residents of the largest category at the outset of the program. Further, while the data from the last decade cannot illuminate what happened immediately following the pollock and halibut rationalizations, it does reflect that there is not a trend of continuing transfers of revenue share out of small communities.

To examine whether smaller communities are disproportionately concentrating revenues on fewer vessels, Figure 7 shows the natural logarithm of average community-level HHIs of vessel revenue within each of six size categories. The figure reveals a trend of increasing vessel revenue concentration within communities of every size relative to 2004. Mid-sized cities of 7,500–25,000 people are most stable, and medium-small cities of 1,500–2,500 people, which saw a significant decrease in the number of active vessels during the study period, saw the greatest increase in concentration. What we do not see, however,

Number of Active Vessels by Region

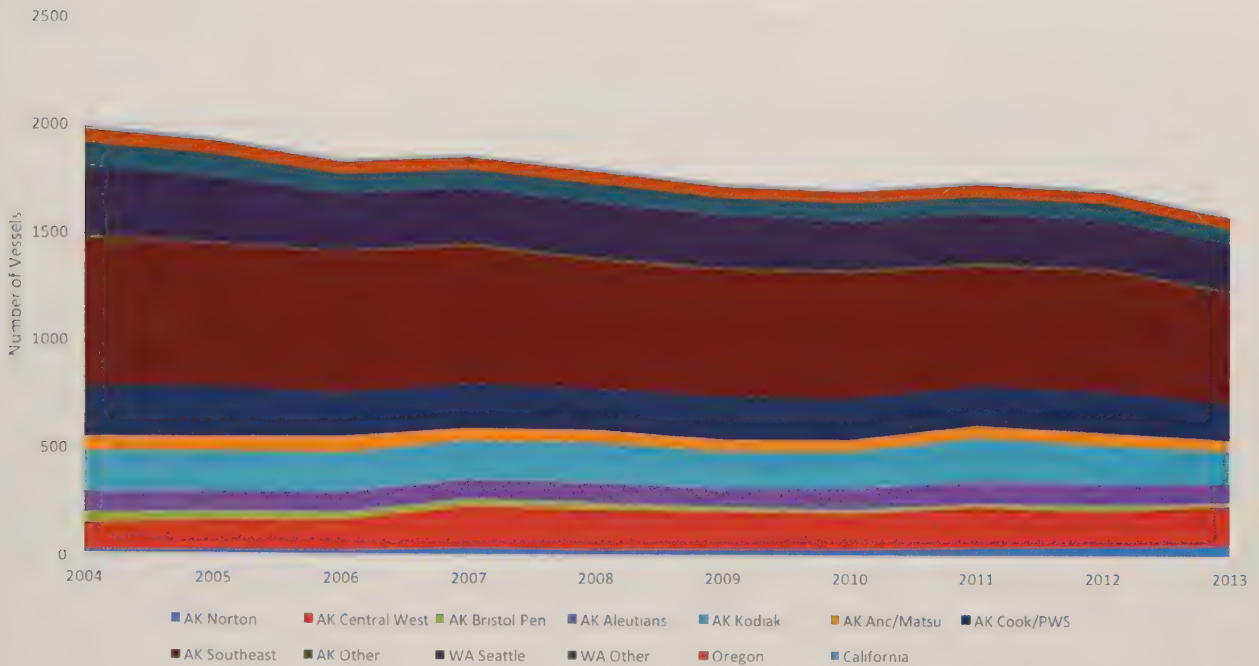


Figure 4.—Number of active vessels with revenue in some fishery in each region.

is a consistent pattern of small communities exhibiting greater or lesser degrees of diversification relative to larger communities. Rather, the smallest communities saw a sustained decrease in revenue concentration during 2006–10, reflecting a decreased share of halibut revenue as TACs declined, which is more recently being offset by increased village-based ownership of crab and pollock vessels, supported by CDQ ownership.

Although the revenue for these smallest communities may be stabilizing, our analysis of revenue flows does not illuminate the actual community-level impact of substituting a loss of direct revenue from individually owned vessels fishing halibut with indirect payments from increased CDQ ownership of larger vessels. This latter source of revenue is likely to provide much less direct benefit such as community block grants, crew employment opportunities, and increased local processing capacity.

To explore differences among com-

munities within the same size category, Figure 8 presents violin plots representing the distribution of individual communities' vessel-revenue HHIs. The white dot in each violin indicates the median, the black bar the inner-quartile range, and the width of the gray field the smoothed density at that HHI; smoothing is required to protect confidentiality in communities with fewer than three vessels. Although these distributions are typically bimodal—reflecting numerous communities with one vessel—the changes in the median and positive mode can nonetheless be informative. There is no evidence of a median increase in concentration in cities between 1,500–2,500 and 25,000–250,000, even though some individual communities within those size bins may have exhibited some change. Small cities (under 1,500) show decreasing revenue concentration, while medium-sized cities show flat to increasing (especially 7,500–25,000) revenue concentration, meaning their owner income is con-

centrated on fewer vessels. Increasing diversity in smaller cities could reflect participation in a greater range of fisheries or that they are losing some market share in the fisheries that made up the largest shares of their income.

Surprisingly, there is increasing concentration in medium-sized cities. There are several possible reasons that it may be easier for small operators to leave fishing in somewhat larger communities. First, it may be easier for large owners to buy out quota or permits from owners in medium-sized cities because they want to minimize transaction costs of acquisitions, and fishermen from medium-sized cities may have larger bundles of quota that are more appealing to large operators. Second, harvesters in medium-sized cities may have better outside (potentially non-fishing) labor market opportunities that make it more feasible for them to discontinue commercial fishing. Third, diversity in smaller western Alaska communities may be supported by CDQ corporations, whose missions

Regional Diversification Across Vessels

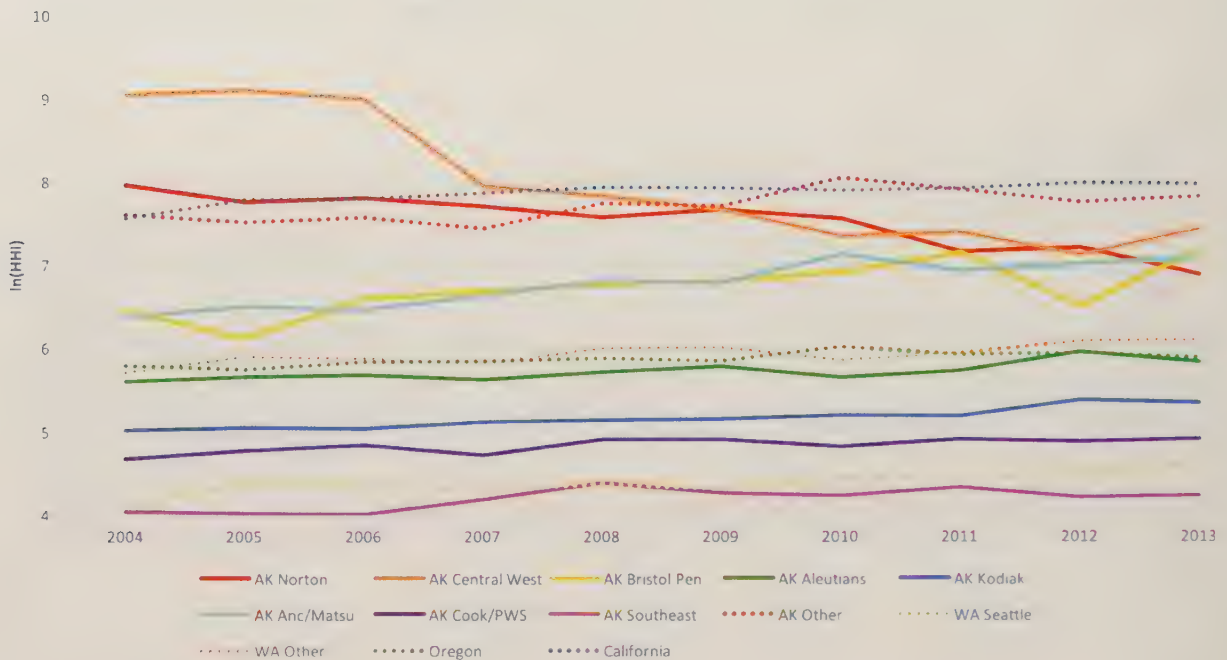


Figure 5.—HHIs reflecting the diversity of revenue across vessels owned in the region.

may lead them to attenuate the concentration trend that would otherwise prevail given their community size.

The aggregate analysis does obscure some variation in individual fisheries. In the newly rationalized crab fleet, the shares are largely stable although the smallest communities show slightly smaller shares, while the largest cities gained roughly 5%. In the years immediately following crab rationalization, there was a more dramatic shift towards large cities, but in recent years communities with populations from 2,500 to 25,000 have gained share. The salmon fishery shows increasing revenue shifting to towns from 2,500 to 7,500 in population, with the gains coming from communities of “population size unknown”⁴. This fishery is the most diverse in terms of distribution of revenue by population size, and large cities are not dominant. In the halibut CDQ fishery there is a large

degree of volatility once again, and the smallest communities have a much larger percentage of revenue in 2013, while participation across the spectrum has become more diverse (see Supplemental Material for individual fleet plots).

Concentration of Vessel Operations Within Fisheries

Up to this point in our analysis we have seen a relatively stable distribution of revenue across regions and within most community size classes. However, we have not examined whether particular vessels are becoming more concentrated in the fisheries that they pursue. That is, the observed stability may reflect that vessels could make similar amounts of revenue as in the past, but this revenue could be derived from a different and less diverse set of fisheries. This scenario could be disadvantageous if vessel owners are less able to distribute risk from stock fluctuations or market shocks by participating in multiple fisheries

(Kasperski and Holland, 2013). However, Figure 9 does not reflect much variation in the concentration of individual vessel revenues across fisheries. Therefore, at an aggregate level, vessels are not being squeezed out of individual fisheries, at least in ways that they are not able to replace by participating in other, new fisheries.

Discussion

The waters off Alaska host a range of valuable, relatively stable, and healthy fisheries providing immense value to the industries they support and to the U.S. economy as a whole. Examining the participating fleets and their revenue streams over the past decade suggests that real revenues have been growing and that over 60% of the revenues generated are associated with vessels whose owners reside outside of Alaska. Trends in non-Alaskan ownership are stable, however, reflecting historic interests particularly in the pollock, Amendment 80, and crab fleets.

⁴This may be an artifact of improved data quality and fewer “unknown” observations.

We analyze trends in revenues within the fleets along with changes in concentration in fishery participation across various dimensions to see if fishery enclosure policies have affected the spatial concentration of fishery revenues or the distribution across community types. In contrast to what some of the literature and stakeholder sentiment suggest—that limited access, catch share programs, and the forces of modernization cause local harvesters from small fishing-dependent communities to consistently lose revenue to those with more capital from large cities out of state—our results show a more nuanced picture.

From 2004 through 2013, there has been no dramatic trend of revenue or vessel transfer from rural Alaska to Seattle; although the total number vessels especially in southeast Alaska and the Bristol Bay and Peninsula are decreasing. One interpretation is that a major effect of management’s efforts toward enclosure has been to regulate the flow of effort and owner-

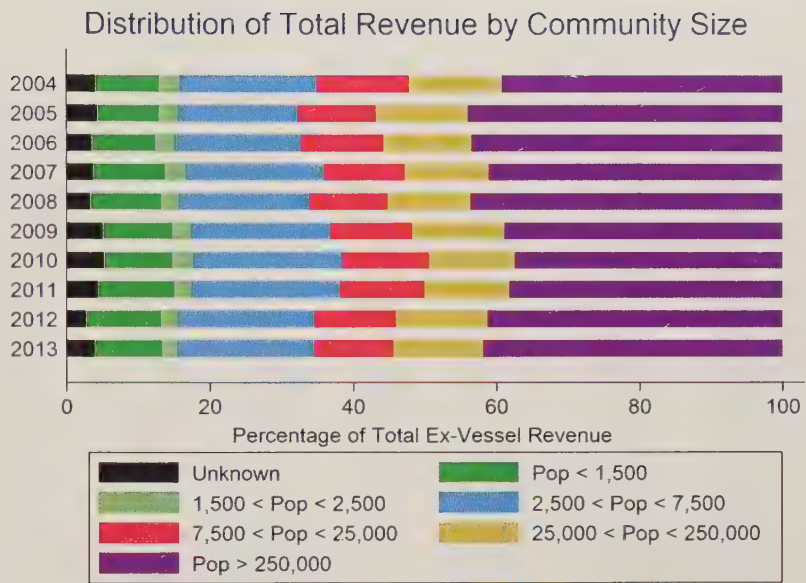


Figure 6.—Distribution of total ex-vessel revenue by the size category of the vessel owner’s city.

Community-Size Category Diversification Across Vessels

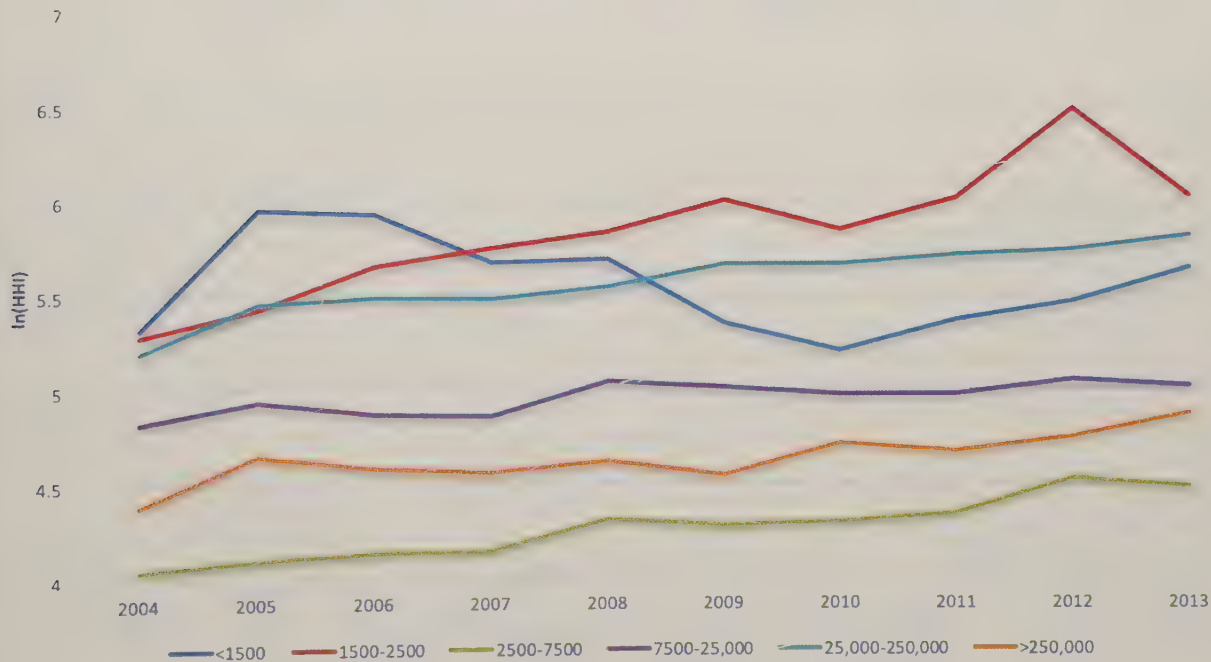


Figure 7.—HHIs of vessel revenue among communities of different sizes.

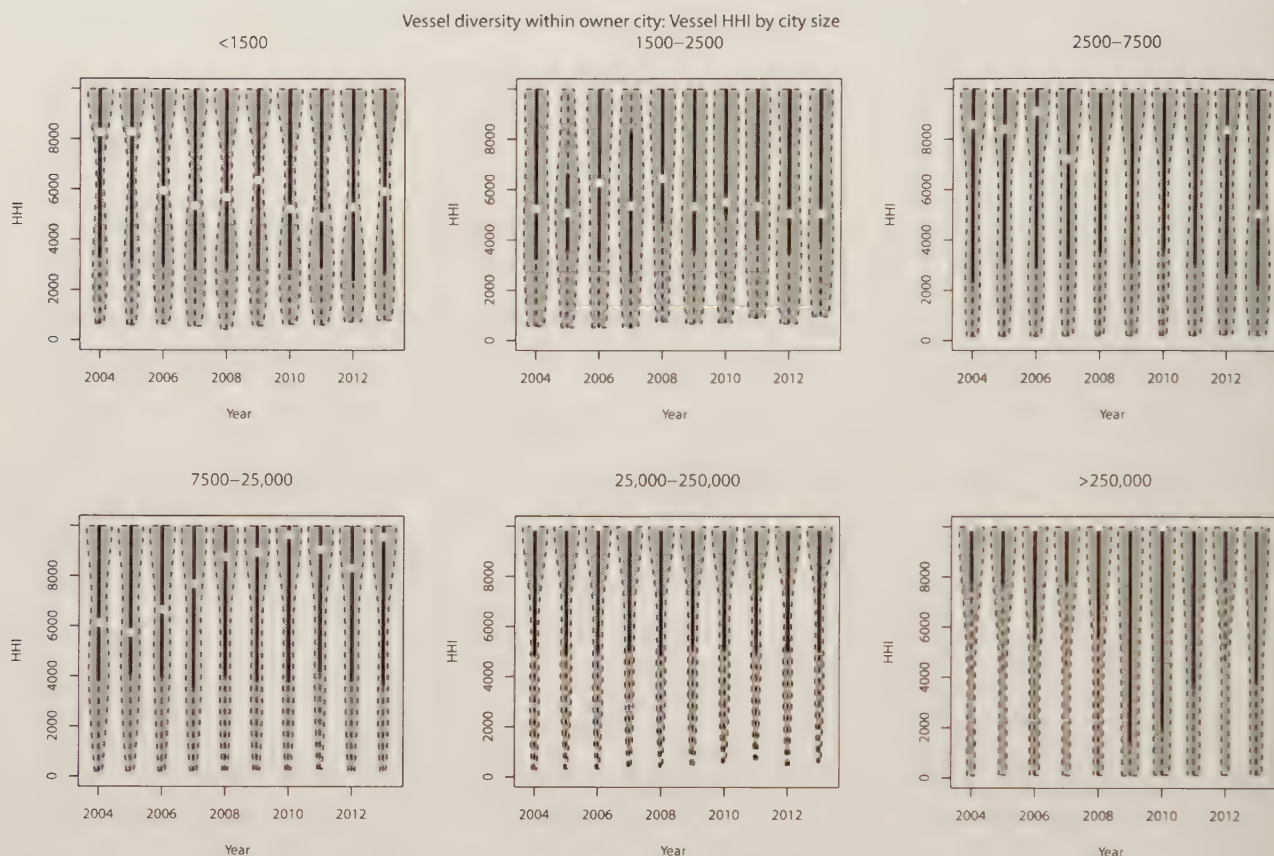


Figure 8.—HHI of ex-vessel revenue within each vessel owner city grouped by city size.

ship into fisheries, which in turn has stabilized the harvesting sector across fisheries.

The revenue share of the Seattle MSA fluctuates more than that of other regions, largely following the trends of the pollock stock during the period we study. In addition, there is no strong evidence that catch shares are forcing rural regions into a shrinking pool of low-value fisheries, because most regions are as diversified across fisheries as they were at the beginning of our sample.

We did find that some regions are becoming increasingly concentrated and reliant on the revenue generating capacity of a smaller set of vessels, which is likely a result of consolidation in the number of harvesting operations. Understanding the economic and social implications of this consolidation requires further data collection

and is unfortunately beyond the scope of this analysis.

Knowing that regional stratification could obscure transfers from small and vulnerable communities to larger ones within the same region, we also examined the distribution of revenue across community sizes. Again, we found no strong trend of consolidation into large cities. There was evidence that the share of the smallest communities is slightly lower than in 2004, while the largest cities have gained share since 2009. Interestingly, the individual communities with <1,500 people show decreasing revenue concentration, while medium cities show flat to increasing revenue concentration suggesting that ownership transfers are occurring in medium-sized communities. This could be attributed to reduced transactions costs or increased outside labor market opportunities in

medium-sized communities or the actions of CDQ groups in the smallest communities.

That our regional aggregate revenue analysis finds little evidence of spatio-temporal revenue redistribution across community sizes or regions may at first seem inconsistent with the literature on community dynamics following rationalization. There are two possible explanations. One is that the community-level dynamics occur partially, and only immediately following enclosure policies. Since we do not observe the initial impact of rationalization in the halibut/sablefish fleet, it is possible that there was a rapid consolidation of revenue outside Alaska that is beyond the scope of our data range. This is not supported by results from the 20-yr review of the halibut and sablefish IFQ program which suggest that while community-level

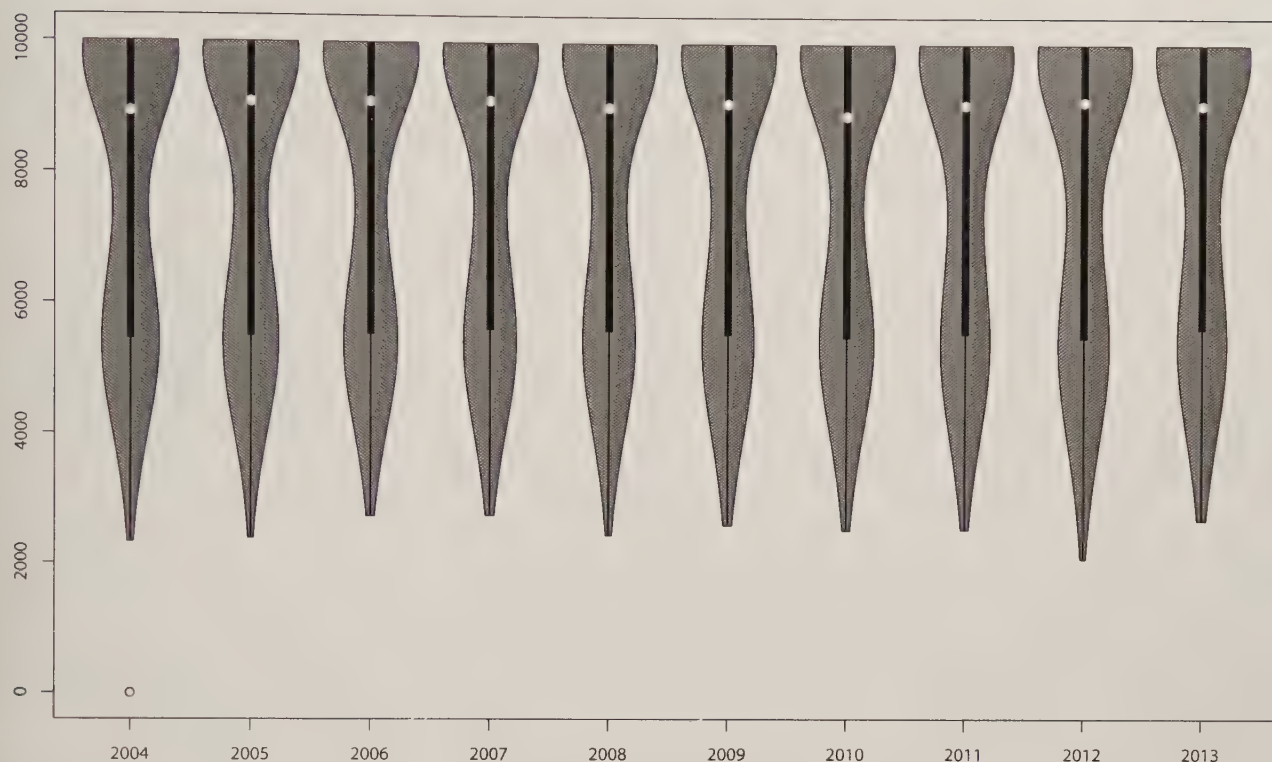


Figure 9.—Distribution of individual vessel HHIs across fisheries.

engagement in the harvesting sector varied across specific southeast Alaska ports, quota share ownership by Alaskan residents has been largely stable in these fisheries since implementation (NPFMC, 2016b:399).

Another possibility is that the CDQ program—the primary policy instrument designed to address the divestment in fishing activity in rural western Alaska—has been effective. Evidence in favor of the latter interpretation is that the most prominent regional trends are attributable to acquisition of quota and vessels by CDQ groups. This is especially relevant in the regions where the groups have focused on increasing their ownership stake in vessels and buying up quota shares. These actions may contribute direct revenue when local residents have the capital to participate directly, such as the halibut fleet, or less direct benefits in fleets such as crab and pollock. In our data, these actions

translate as increasing dependence on a smaller number of fisheries, but also increased participation and local revenue.

Although the CDQ groups by definition represent rural western Alaska interests, it is possible that there are small operators within their boundaries who are unaffiliated with CDQ groups or small communities in southeast Alaska outside their boundaries who have not shared in the success of these groups. These groups may have seen their market share diminish through quota acquisition by those with greater access to capital, including both the industrialized fleets and the large CDQ corporations.

This exploratory study is primarily descriptive of trends and change in the distribution of revenues; however, it suggests several further avenues for analysis. First, it is important to note that this analysis does not construct a proper behavioral counterfactual that

isolates the effects of management changes, before or during the period analyzed; it is unlikely the distribution of revenue would remain today what it was in 2004, given changes in fish stocks, technology, and the regional and global economies.

Second, our focus on linking revenue to vessel owner removes the complexities associated with non-fishing quota owners, who in many fisheries capture a significant portion of the fishery rent to spend in their residential communities. Location of residence need not have any relationship to the vessel's registration or area fished. Linking our analysis with information on quota ownership and transfers would clarify the extent to which vessel owner activity is reflective of the distribution of fishery benefits in quota fisheries.

While fisheries management, and even different participants in the management process, may have different objectives in implementing catch

share programs, our results suggest that the primary distributional effects of the North Pacific Fishery Management Council's policies have been to stabilize participation in the fishery from 2004 to 2013. Indeed, the most dramatic shifts in revenue distributions during the study period were the reduction in vessel participation following rationalization in the crab fishery and the unexplained decline in the halibut TAC, neither of which resulted in changes in the distribution of revenue in the regions most affected. Thus, if the intent of these policies was to institutionalize the historic patterns of participation by incumbent harvesters, they have been largely successful.

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Exempted Testing of Deep-set Buoy Gear and Concurrent Research Trials on Swordfish, *Xiphias gladius*, in the Southern California Bight

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Introduction

The swordfish, *Xiphias gladius*, is a highly migratory species that supports vast fisheries around the globe (Ward et al., 2000). In addition to annual migrations that may span thousands of kilometers in a single season, swordfish also exhibit daily vertical movements that transition from surface waters at night to those below the thermocline during the day (300–1,000 m; Carey and Robison, 1981; Carey, 1990; Sepulveda et al., 2010; Dewar et al., 2011). Over the past century, swordfish fisheries have evolved to capitalize on this behavior pattern, with most fishing activity occurring at night, within the waters of the upper mixed layer (above the thermocline) (Ward et al., 2000).

Among the gear types currently used to target swordfish in the North Pacific, shallow-set longline has become the most common harvest method followed by drift gillnet and harpoon op-

erations, with the latter two fisheries only occurring in a few select locations (Hanan et al., 1993; Coan et al., 1998; Ward et al., 2000). Although swordfish are more accessible near the surface at night, this time and depth also results in high spatial overlap with non-target species (Beverly and Robinson, 2004; Gilman et al., 2006; Sepulveda et al., 2014). In particular, shallow-set swordfish fisheries have been routinely scrutinized by conservation groups for their lack of selectivity and high incidence of interaction with species of special conservation concern (i.e., sea turtles, marine mammals, and sea birds; Gilman et al., 2007).

Within the exclusive economic zone off California (CA EEZ), the primary gear type used to harvest swordfish is the California drift gillnet (DGN), a technique that has received regulatory scrutiny over its lack of selectivity and past history of interactions with species of special concern (i.e., marine mammals and sea turtles; Carretta et al., 2004). Over the past three decades, the DGN fleet has declined to historic lows in participation, landings, and revenue, with recent interactions with protected species threatening further

restriction (NOAA, 2001, 2014; Martin et al., 2015; Urbisci et al., 2016).

Historically, options for reducing bycatch in the DGN fishery have primarily focused on gear modifications (i.e., acoustic pingers, extended surface suspenders) and the use of seasonal closures to reduce spatial overlap with sensitive species (i.e., leatherback sea turtles, *Dermochelys coriacea*; Carretta et al., 2004; Martin et al., 2015; Eguchi et al., 2016). Although effective, these restrictions have severely limited the temporal and geographic scope of the DGN fishery, with most of the fishing activity now consolidated to the U.S. portion of the Southern California Bight (SCB), a body of water that extends from Point Conception (34° 27' and 120° 28') to below the Mexican border and out to 300 km (Daily et al., 1993). Despite the decline of west coast swordfish operations, local demand continues to exceed domestic production, a scenario that further fuels the U.S. Pacific coast's reliance upon foreign fleet imports for meeting local consumption needs (Rausser et al., 2009).

Given the suppressed state of this swordfish fishery, recent management

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ABSTRACT—Research and exempted fishery trials were performed off the U.S. west coast using deep-set buoy gear (DSBG), an artisanal gear type designed to target swordfish, *Xiphias gladius*, below the thermocline during the day. All trials were performed within the Southern California Bight (SCB) under an exempted fishery permit (EFP) recommended by the Pacific Fisheries Management Council (PFMC) and authorized by the National Marine Fisheries Service (NMFS). Six cooperative fishermen were outfitted with uniform gear sets and performed 344

standardized deployments (10 individual buoys deployed for 8 h) which produced 2,795 buoy soak hours. The collective catch resulted in a marketable catch rate of ~97%. Swordfish comprised >80% of the total catch, with 611 individuals harvested over the two seasons of the EFP. Bigeye thresher sharks, *Alopias superciliosus*, were the second most common species totaling ~16% of the EFP catch. The average daily swordfish catch rate was 1.75 swordfish/8-h set and varied by year and cooperative vessel. Catch rates and composition were similar to previous and

concurrent research findings and contrasted shallow-set nocturnal buoy gear experiments performed during the same seasons. Nocturnal shallow-set research trials performed adjacent to EFP activities revealed low target (~9% swordfish) and high (>80%) non-marketable catch. Juvenile blue sharks, *Prionace glauca*, made up >76% of the total nocturnal catch. Collective DSBG trials to date suggest that daytime deep-setting within the SCB may provide an additional opportunity for west coast fishermen to access a domestic resource.

priorities have focused on the development of alternative harvest methods to increase domestic production and fisherman opportunity (Sepulveda et al., 2014). Fishery development within the CA EEZ is complicated by high conservation standards and the sensitivity associated with several of the bycatch species that spatially overlap with swordfish (e.g., leatherback and loggerhead, *Caretta caretta*, sea turtles as well as several marine mammals).

Other issues that have suppressed west coast fishery development include the continued prohibition of pelagic longline gear within the CA EEZ (O'Brien and Sunada, 1994; West Coast Highly Migratory Species Fishery Management Plan, HMS FMP¹). This prohibition has prevented the development and social acceptance of shallow-set longline, the most common method used to harvest swordfish worldwide (Ward et al., 2000). Collectively, these conservation concerns have negatively impacted local swordfish production and continue to hinder the development of alternative methods for harvesting a domestic resource within the CA EEZ (Urbisci et al., 2016; Sepulveda et al., 2018).

In response to the decline in fishery participation and in accordance with Federal mandates (Magnuson-Stevens Fishery Conservation and Management Act, as amended²), the Pacific Fishery Management Council (PFMC) prioritized the development and trial of alternative methods for harvesting west coast swordfish. Among the gears proposed was deep-set buoy gear (DSBG), an artisanal "hook and line" technique developed for targeting swordfish within the SCB (Sepulveda et al., 2014). DSBG uses depth to selectively target swordfish below the thermocline during the day, a strategy that has been shown to reduce non-target interactions in several deep-set longline fisheries around the world (Beverly and Robinson, 2004; Gilman et al., 2006, 2007).

Off California, deep-setting is of particular interest given that the waters are highly stratified with a relatively shallow thermocline (20–70 m; Palacios et al., 2004) and oxygen minimum layer (350–400 m; Levin, 2003; Bograd et al., 2008). This suite of environmental conditions has been proposed to compress the amount of suitable habitat available for pelagic fish species, which may lead to enhanced targeting opportunities and gear performance (Prince and Goodyear, 2006).

Although DSBG has been shown to be effective at selectively targeting swordfish within the SCB (Sepulveda et al., 2014), questions concerning economic viability and cooperative interest remain untested. Additionally, it was unknown how DSBG catch and performance metrics produced under previous research application compared to commercial operations. Therefore, this study focused on 1) the field testing of DSBG by cooperative fishermen operating under an exempted fishery permit (EFP) recommended by the PFMC and issued through NMFS, and 2) expanding the scope of fishery development research for swordfish off southern California. Specifically, this work tested hypotheses related to the economic viability and catch performance of DSBG using data from six cooperative fishermen operating off the Southern California coast. Findings are presented and compared with concurrent research trials performed by the Pflieger Institute of Environmental Research (PIER). Collectively the body of work presented in this study is focused on the development and revitalization of the U.S. west coast swordfish fishery.

Materials and Methods

All cooperative fishing trials were performed under an exempted fishery permit (EFP) issued to lead investigator C. Sepulveda (PIER) through the PFMC on 18 of Aug. 2015 (PIER DSBG-EFP). EFP protocols were based on previous gear research and development trials conducted by PIER from 2011 to 2014 (Sepulveda et al.,

2014). All deployments, gear rigging, and set protocols followed the terms and conditions outlined in the PIER DSBG-EFP. Set locations were performed within the eastern portion of the SCB between Point Conception and the Mexico border (Fig. 1). All research experiments were conducted under a NMFS Letter of Acknowledgement issued by the NMFS West Coast Regional Office and a California Department of Fish and Wildlife (CDFW) Scientific Collection Permit (SPC-2471). To reduce seasonal variation the research trials presented in this work were performed concurrently with the PIER DSBG-EFP from 2015 to 2017, with catch being tagged and released (i.e., research catch did not contribute to EFP landings).

Cooperative Fishermen Selection

Cooperative fishermen participating in the PIER-DSBG EFP were chosen based upon a selection rubric for participation. Criteria used in the selection process included: availability during the primary California swordfish season (July–December), previous swordfish experience, willingness to cooperate and work as a unit, agreement to abide by all PIER and EFP mandated terms, and willingness to participate throughout the season regardless of gear performance. Selected participants had at least 10 years of swordfish fishing experience off California and an average participation history of 20 years. Cooperative fishermen also had valid swordfish permits, no recent history of fishing violations, and agreed to carry observers without objection. Based on the EFP terms and conditions, the EFP manager (PI Sepulveda) was held equally liable and responsible for the actions of the EFP participants.

Deep-set Buoy Gear

The DSBG design used in this study has been described previously in Sepulveda et al. (2014). For all cooperative fishermen participating in the PIER-DSBG-EFP, all sets of gear were designed by the EFP manager and measured to the nearest meter to

¹<http://www.pcouncil.org/wp-content/uploads/2016/03/HMS-FMP-Mar16.pdf>

²http://www.nmfs.noaa.gov/sfa/magact/MSA_Amended_2007%20.pdf

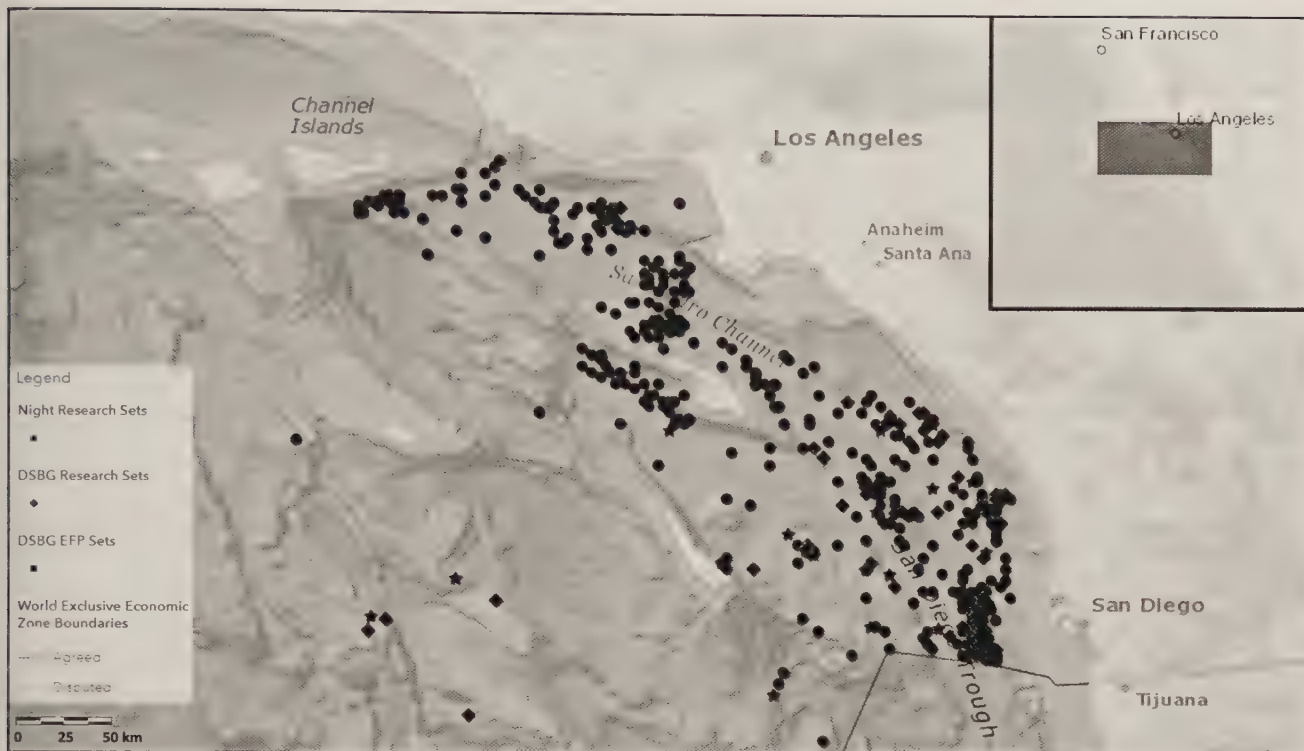


Figure 1.—Map of the Southern California Bight showing research and exempted trial deployments of deep-set buoy gear (DSBG) from June, 2014 to January, 2017.

ensure comparable rigging and performance. Briefly, the gear configuration consisted of a three-float system which included two strike-indicator floats (3.2 kg) and one large non-compressible longline float that was labelled with the vessel information (21 kg; 36 cm dia.) (Sepulveda et al., 2014). The float system was affixed to a high-flyer flag and at least one form of locating device (i.e., radar reflector, strobe) to prevent gear loss and facilitate location at night.

Each piece of DSBG was designed to fish between 250 and 350 m with a terminal weight (3.6 kg) attached to each piece of gear. Gear sets were measured and configured by the PIER team prior to delivery to the EFP participants. Fishermen were given the option to fish up to a maximum of three hooks per individual piece of gear with a maximum of 10 individual pieces deployed at one time (maximum of 30 hooks soaking simultaneously). Gangions were approximately 8 m long and constructed

of 1.8 to 2.0 mm monofilament leader with a crimped 18/0 circle hook (Mustad model 39960DT³). Battery-operated illumination (Power Light, SNL Corp., Florida) was used proximal to each gangion with fishermen given the choice of colors to be used (most deployments used either green or blue). Bait type consisted of either squid, *Illex* spp., or finfish such as chub mackerel, *Scomber japonicus*.

Observation and EFP Monitoring

Field observation of EFP activity was sourced through Saltwater Inc., Seattle, Wash., an independent fishery observer staffing contractor. Based on PFMC and NMFS terms and conditions, all EFP activities were to be monitored at a minimum rate of 30%. The 30% coverage rate was granted for this study in response to 1) previous research trials which had docu-

mented DSBG catch composition over the previous four years (Sepulveda et al., 2014), 2) the need for increased EFP effort and budget constraints, and 3) the additional monitoring and guidance provided by the EFP manager. To enhance data quality and increase confidence in reported catch during unobserved trips, the EFP coordinator required each vessel captain to comply with additional reporting requirements. These included deployment and return check-ins with NMFS, CDFW, and PIER as well as a daily catch reporting requirement. Daily reports were logged and compared to both vessel log sheets and landings records (see below section Catch and Bycatch Estimation).

Observer placement criteria consisted of initial assignment at the beginning of the season to build a coverage base for each vessel and subsequent assignment to a vessel if coverage reached a level of 35% to prevent vessels from falling below the minimum EFP coverage rate. Other consider-

³Mention of trade names or commercial companies is for identification purposes only and does not imply endorsement by the National Marine Fisheries Service, NOAA

ations for carrying an observer included mandatory placement if the DGN gear type was going to be fished on the same fishing trip. Lastly, vessel operators could not decline the placement of an observer for any reason.

Custom observer and vessel log sheets were designed in conjunction with the NMFS Fisheries West Coast Observer Program coordinator (C. Villafana, NMFS-West Coast Region, WCR) to capture additional environmental information associated with deployments. Landings were monitored using traditional CDFW landings receipts, logbook records, and identification tags affixed around the collar of landed catch. Identification tags were instituted in year two of the EFP and contained a product code and vessel name that allowed consumers to better track DSBG product as it moved through the market chain. Identification tags were instituted in response to market and consumer requests voiced in year 1 of the EFP.

EFP Deployment Conditions

In an attempt to mimic commercial fishing conditions to the extent possible, cooperative fishermen were given the liberty to deploy DSBG when and where they wanted as long as the configuration of the gear was not altered and deployment location fell within the action area of the terms and conditions of the PIER-DSBG-EFP. Daily set location, duration of set, and quantity of gear deployed was left up to the discretion of the EFP participant. In accordance with the EFP terms and conditions, DSBG could not be deployed prior to sunrise and the participant had to commence gear haul-back procedures prior to sunset, thus providing a theoretical maximum set duration.

Catch and Bycatch Estimation

All catch was enumerated using both vessel and observer log sheet entries and CDFW landings receipts. Vessel log sheets were compared with check-in reports and observer logs to ensure that fishing dates and times, catch statistics, and non-target species interactions were consistent. If discrepancies

were identified, then individual fishermen were contacted directly to confirm or correct uncertainties (for the entire 2 year EFP (4,084 buoy deployments) this was estimated to be less than 8 instances). Target and non-target catch rates were summarized from actual data and reported to management agencies in both raw and standardized form. Standardization was performed to account for short sets (1–3 h) and to allow for effort comparisons among other gear types (i.e. longline and DGN soak times) as well as previous DSBG fishing trials (Sepulveda et al., 2014). The standardized set metric defined a fishing day as 10 pieces of buoy gear fished over an 8-h period, which closely approximated average deployment parameters for both the EFP and research trials.

Non-target species catch was further classified into either marketable or non-marketable species (i.e., species that did not have a market history off the west coast) to assess DSBG selectivity and potential discard rates. Estimates for sensitive species bycatch, including marine mammals and species with extended federal or state protection (i.e., threatened or endangered), were calculated for both observed and extrapolated values. The extrapolation procedure took into account total effort (number of set days) and observer coverage rates to generate the extrapolated bycatch estimate. Extrapolation procedures were also performed for other non-marketable species (i.e. blue sharks, *Prionace glauca*; Table 2) and not used for marketable catch, as the reporting statistics were validated with landings receipts and presumed to be accurate for marketable species (Urbisci et al., 2016).

Research Sets

In addition to the EFP deployments, DSBG research trials were conducted off southern California by PIER onboard the research vessel R/V *Malolo* from June 2014 through December 2016 to further evaluate gear performance, test for differences in day vs. night catch composition, and to conduct tagging experiments. Initial

DSBG research and development trials conducted from 2011 to 2013 were analyzed separately for catch composition and effort (Sepulveda et al., 2014). As with previous experimental deployments, most of the research sets utilized three hooks per piece of buoy gear. Based on EFP terms and conditions, experimental DSBG catch and effort metrics were calculated and reported independent of the cooperative EFP trials (PIER DSBG-EFP).

In addition, concurrent nocturnal shallow-set experiments (shallow set buoy gear, SSBG) were conducted within the same areas and times as the daytime PIER research trials and EFP deployments. Nocturnal catch data were recorded using the same logbook forms and used to compare catch composition between deep-day and shallow-night setting. Similar to the DSBG deployments, night set depths were based on swordfish movement data from the study area (Sepulveda et al., 2010, 2014) and traditional swordfish longline methods currently used outside of the CA EEZ. Circle hooks (18/0 Mustad model 39960DT) were positioned within the upper mixed layer at night (between the surface and the thermocline; 10 to 60 m) with a mean hook depth of ~24 m. Hook depth was verified by a depth logger that was affixed to each gangion (CEFAS Tech. Ltd.; Lowestoft, U.K.). Nocturnal sets were constructed of the same gear and materials used in the daytime trials (DSBG), as one of the goals was to assess feasibility of concurrent shallow and deep-set deployments (DSBG).

The shallow-set configuration was very similar to the DSBG design with less vertical mainline and a shallower hook position. The configuration used 3.6 kg weights, strike indicator buoys, and an illumination source proximal to each branched 8 m gangion (1.8 mm monofilament). Terminal gear was similar to that used in the DSBG trials except that the terms and conditions of the research trials precluded the use of squid for any shallow set experiments. Set location parameters were based on daily cooperative vessel input and were principally conducted in areas of

temperature and productivity convergence (Sepulveda et al., 2014).

Each nocturnal set consisted of 10 to 30 hooks deployed for a minimum of 4 h between the hours of sunset and sunrise. For comparison with the PIER DSBG-EFP and research trial data, night sets were standardized based on an 8-h soak period. Similar to daytime DSBG efforts, gear was actively monitored for strikes and serviced upon detection of a fish on the line. If catch was detected, gear was hauled and the catch was measured, tagged with either a conventional or electronic tag, and released. Bait predation was documented at the time of haul-back for all research sets and was defined as any instance in which 50% or more of the bait was mutilated or consumed during the soak period.

Data Analyses

Monthly logbook entries were entered into an Excel spreadsheet and summarized by vessel prior to generating collective summaries. Only catch that was retained for sale or released at the vessel were considered in the catch assessments. To provide a consistent and comparable estimate of fishing effort, data was examined by the number of sets, buoys deployed, and soak hours to calculate the number of "standardized" set days. The 10 buoy and 8-h standardized metric was chosen because it closely mirrored the daily average soak time and number of buoys deployed for the entire PIER DSBG-EFP. It also provided a consistent set metric for comparing research and EFP activities. Market price estimates were based upon average ex-vessel price recorded by the cooperative fishermen at the time of offloading.

Economic Analyses

To preliminarily assess the cost of DSBG activities while under exempted testing, a survey was provided to cooperating fishermen following the Year 2 trials. The survey was voluntary and consisted of a series of questions aimed at estimating the daily expenditures associated with a typical DSBG

fishing day. Vessels were excluded from the analysis if vessel size was not consistent with the size range likely to participate in a commercial DSBG fishery, if the vessel did not participate in the EFP throughout the entire season, or if they were reluctant to provide financial information.

Responses from participating vessels were averaged among the group to ensure anonymity and daily cost estimates were based on the average number of set days per vessel in Year 2 ($n = 56$). Because cooperative fishermen participating in the EFP are portfolio fishermen who participate in several independent fisheries throughout the year, fixed costs (i.e., insurance, slip fees) were considered only for the swordfish fishing season (6 mo, July–January). Also, given that all of the participants own their vessels outright, vessel financing was not considered in the cursory analyses. Given that all fishermen sold to the same market and because price did not vary considerably among EFP vessels, average fish price was not weighted. Estimates of daily and seasonal profits were also not calculated given that trip length varied widely and because gear set-up was subsidized through the projects funding sources.

Tagging

To assess short-term vertical movements of the primary non-marketable species encountered during nocturnal research trials, two blue sharks (1.4 to 2.1 m (fork length) FL) were tagged with short-term satellite tags (Wild-life Computers, Richmond, Wash.; Mini-Pat) prior to release. Tags were programmed for <30 days to ensure that all the archived time-series data could be transmitted through the Argos Network and data resolution was sufficient to compare diel movement patterns between target (i.e., swordfish) and non-target species (i.e., blue sharks). The depth statistics from the blue shark tags were compared with the tracks from two tagged swordfish (130 and 152 cm FL) that were also tagged within the same geographic area and season.

Results

PIER DSBG-EFP Effort and Location

This work reports on the first two seasons of exempted trials of DSBG aboard cooperative vessels from 2 Sept. 2015 through 10 Jan. 2016 (Year 1) and from 25 May 2016 through 9 Jan. 2017 (Year 2). Fishing effort and distribution was constrained by the terms and conditions of the PIER DSBG-EFP. Set locations occurred primarily in the south and eastern portion of the SCB, from Point Conception, CA (34° 27' N and 120° 28' W) to the Mexican border (Fig. 1).

Overall six cooperative fishing vessels participated in the initial two years of the EFP, with four vessels participating in Year 1 and five fishing during Year 2. In Year 1, vessels were not cleared for fishing until late August, which resulted in 95% of fishing effort occurring September through December. In year two, the effort was more evenly distributed throughout the season, with fishing activity spread from July through December. For the two years, (September, 2015 to January, 2017), 417 DSBG set days were reported over the course of 113 independent fishing trips, with a mean trip duration of 3.65 days/trip. During the two seasons, the total number of sets per vessel ranged from 43 to 127 (mean=69.5 sets/vessel) which resulted in a total of 4,084 pieces of DSBG deployed during the study period.

Although cooperative fishermen had the option to deploy up to three hooks per piece of gear, >95% of EFP sets were deployed using only one baited hook per buoy, a strategy that reduced tangling of the upper gangions. The collective EFP activities yielded 27,535 buoy-soak hours, with an average of 9.8 buoys deployed per set. Daily soak times varied by vessel and season with annual averages ranging from 6.3–7.6 h/set; with a collective mean of 6.7 h/set. For comparison purposes, set days were standardized to 8-h soak days or 349 8-h fishing days. To compare metrics of catch per unit effort, the data were also standardized

Table 1.—Annual statistics for the total number of observed and unobserved sets for each cooperative fishing vessel that participated in the PIER deep set buoy gear exempted trials (DSBG EFP) and associated observer coverage rates for the 2015–16 fishing seasons.

EFP Vessel	2015 # set days	2016 # set days	Total # set days	Total # observed sets	Observer coverage rate
F/V <i>Chula</i>	50	0	50	19	38%
F/V <i>Gold Coast</i>	46	81	127	47	37%
F/V <i>Three Boys</i>	28	35	63	26	41%
F/V <i>Spirit</i>	14	45	59	27	46%
F/V <i>Leah Gail</i>	0	75	75	30	40%
F/V <i>Aurelia</i>	0	43	43	21	49%
Total/Mean	138	279	417	170	41%

to a full 10 buoy complement, which yielded a collective effort estimate of 344 8-h fishing days. Over the course of the study, there was only one piece of DSBG lost at sea following a mechanical breakdown aboard one of the cooperative vessels.

Observation and Catch Monitoring

Collectively, 170 set days were observed by NMFS-certified monitors, resulting in an overall observer coverage rate of 41% for the two year EFP period (Table 1). In Year 1, the average coverage rate for the entire EFP group was 46% (range 38–79%) and in Year 2 the average coverage was 38% (range 35–49%). Observer coverage was consistently maintained above 35% on all EFP vessels throughout all EFP deployments.

Catch

During the initial two years of the PIER DSBG-EFP, catch was com-

prised of seven species, with swordfish making up >80% of the total catch. Other marketable species, included opah, *Lampris guttatus*; bigeye thresher shark (BET), *Alopias superciliosus*; mako shark, *Isurus oxyrinchus*; and escolar, *Gempylidae*; which comprised an additional 18.0% of total catch (Table 2, Fig. 2a). Non-marketable catch (i.e., species not typically retained for sale in the California fishery) comprised 1.2% of the total catch and consisted of eight blue sharks and one northern elephant seal, *Mirounga angustirostris*. The northern elephant seal interaction took place during an observed set. The hook was reported to be in the upper lip near the corner of the mouth and the elephant seal was described as “alive and alert” upon release. The observer records also reported that the hook was shed from the animal prior to swimming away. Based on the single elephant seal interaction and a collective EFP observation rate

of 41%, the extrapolated interaction estimate was 2.5 individuals for the study period. Because the northern elephant seal was observed to be “alive and alert” upon release, no further estimates of fishing mortality were calculated. Because there was no observed blue shark catch (i.e. all 8 blue sharks were self-reported during non-observed trips), the extrapolated value for blue sharks was 0.

Collectively, 611 swordfish were caught over the two-year EFP period. Average swordfish size was consistent with ongoing harpoon and DGN operations, with a mean estimated dressed weight of 62.3 kg (range 11–205 kg). Based on mean estimated size, total swordfish landings for the six cooperative vessels was estimated to be approximately 38 t dressed weight, which is equivalent to approximately 48 t round weight (Uchiyama et al., 1999). Average ex-vessel price for swordfish in the PIER DSBG-EFP was approximately \$7.50/lb.

Catch rates varied by vessel and year, with an overall average of 1.75 swordfish/8-h soak period. The non-standardized catch rate for the EFP period based on a reduced soak period was 1.47 swordfish/6.7-h soak. In 2015, daily average catch rates ranged across vessels from 0.6 to 1.6 (mean=1.4 swordfish/8-h set), while in 2016 catch rates ranged from 1.3

Table 2.—Catch statistics (based on actual and extrapolated values) for all deep set buoy gear (DSBG) deployments conducted between June, 2014 and January, 2017 on-board the PIER research vessel and six cooperative fishing vessels that operated under exempted status in the PIER DSBG EFP. Extrapolated catch values are only applied to non-marketable species caught aboard cooperative vessels.

Catch Species	PIER research catch (2014–16)	Research catch (%)	DSBG EFP catch (2015–16)	Extrapolated catch	EFP catch (%)	PIER nocturnal research catch (2014–17)	Nocturnal research catch (%)
Swordfish	59	57.8%	611	NA	80.9%	8	9.4%
Opah	8	7.8%	3	NA	0.4%	0	0.0%
Bigeye thresher	23	22.5%	123	NA	16.2%	1	1.2%
Common thresher	2	2.0%	0	NA	0.0%	0	0.0%
Shortfin mako shark	2	2.0%	1	NA	0.1%	8	9.4%
Gempylidae spp.	2	2.0%	9	NA	1.2%	0	0.0%
Yellowfin tuna	1	1.0%	0	NA	0.0%	0	0.0%
Blue shark	4	3.9%	8	0	1.1%	65	76.5%
Smooth hammerhead	0	0.0%	0	NA	0.0%	2	2.4%
Species with protection							
Northern elephant seal ¹	1	1.0%	1	2.5	0.1%	0	0.0%
California sea lion ¹	0	0.0%	0	NA	0.0%	1	1.2%
Other protected species	0	0.0%	0	0	0.0%	0	0.0%
Total catch (no. of individuals)	102		756			85	
No. standardized 8-h set days	40.5		344				

¹Released alive and alert.

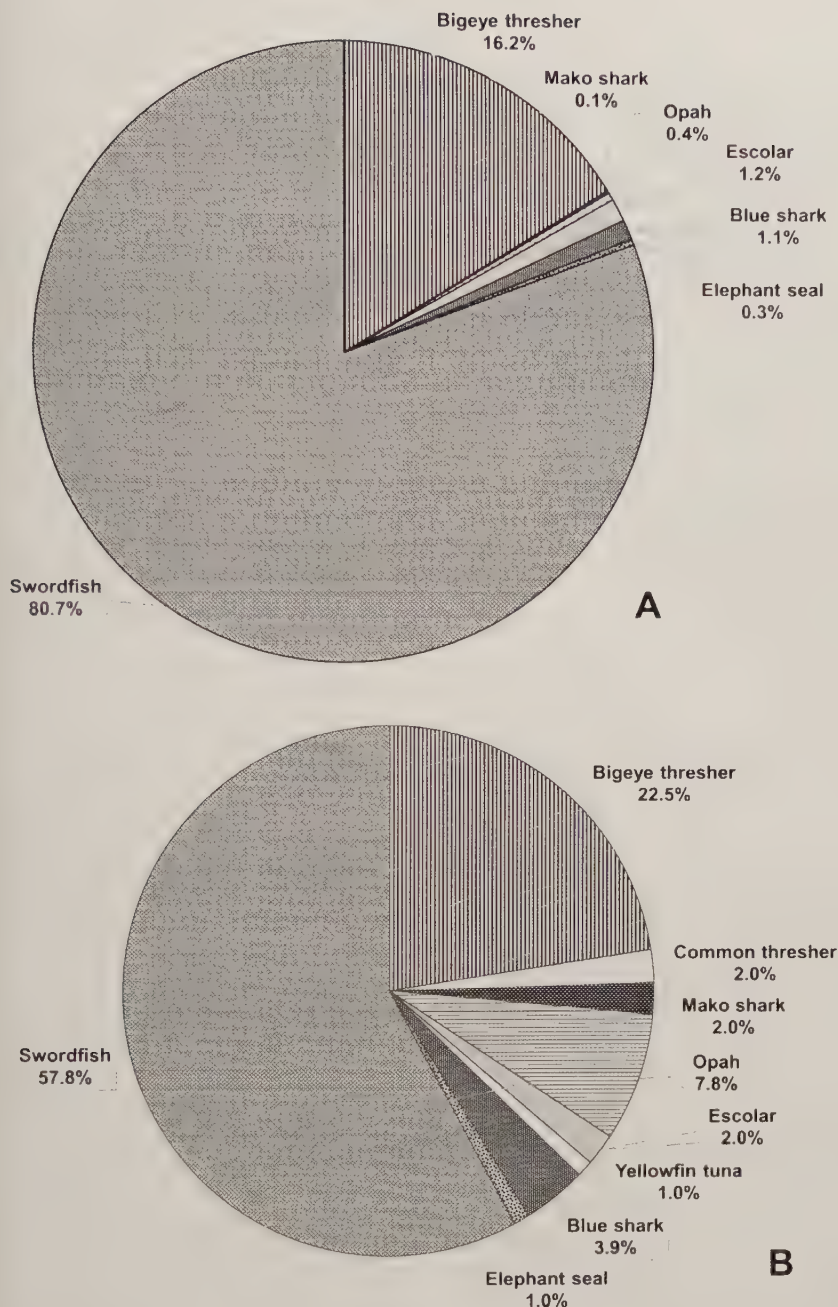


Figure 2.—A. Catch composition for six cooperative fishing vessels during 417 deep-set buoy gear (DSBG) deployments under the PIER DSBG EFP trials throughout the 2015–16 seasons
B. Catch composition of 40.5 standardized 8-hr deep-set buoy gear (DSBG) research deployments within the Southern California Bight onboard the PIER R/V *Malolo* during the 2014–16 seasons.
C. On next page.

to 2.9 (mean=1.9 swordfish/8-h set). In 2015 and 2016 the month with the highest swordfish catch was October.

BET sharks were the second most common species encountered in the 2-yr. EFP and comprised 16.2% of the total catch. BET ranged in estimated weight from 45 to 170 kg, with an average round weight of ~90 kg. Log sheet entries indicated that all BET were alive at the time of capture, and that 76% were released and 24% ($n=29$) were retained for sale. Observer and vessel log sheets indicated that large BET (>100 kg) were typically released, as it was noted that that smaller individuals were more readily handled and marketed. Ex-vessel price for BET ranged from \$0.50 to 3.50/lb, with an average of ~\$2.25/lb. Despite the use of circle hooks, hooking location for BET varied and consisted of the mouth, pectoral fin, and the caudal fin.

Economic Analyses

The average daily operating cost of a DSBG trip day aboard a 13–16 m single engine diesel vessel operating in the PIER DSBG-EFP was approximately $\$477 \pm 79/\text{day}$ (Table 3). Average compensation for a single crew member was approximately $20 \pm 2\%$ of the trip's net profit, and all vessels participating in the survey used only one crew member throughout the EFP period. Based on the average size of fish (62.3 kg or 137 lb dressed weight), average price/lb (\$7.50/lb) and average catch rates for the entire EFP period (1.75 swordfish/8-h day), an estimation of the average daily net income from one day's fishing activity was approximately \$1,087 (daily estimate excludes gear setup, vessel amortization, and travel days; see Methods for more details).

Research Sets

A total of 40.5 standardized (10 pieces of DSBG) 8-h fishing days were conducted aboard the PIER research vessel R/V *Malolo* from 2014 to 2016. Catch composition during PIER DSBG research sets consisted of nine species, which included the same

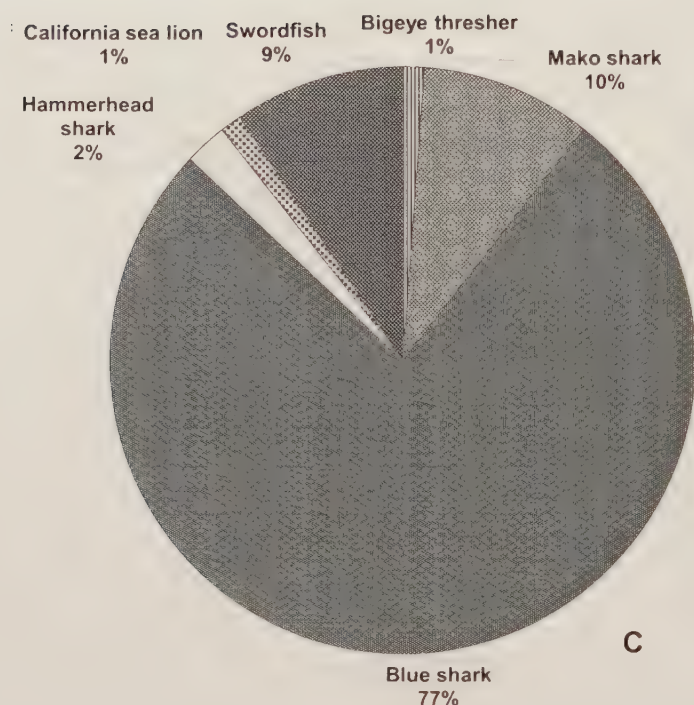


Figure 2.—C. Catch composition from 30 nocturnal shallow-set deployments off southern California onboard the PIER research vessel R/V *Malolo* from 2014–17.

Table 3.—An estimate of daily fisherman expenses based on participation surveys provided by three participants of the exempted trials. Costs reflect daily expenses based on the 2015–16 fishing season (six months) and the average number of days each vessel fished (56 days).

Meals	Mooring costs	Insurance costs	Crew % of trip net ¹	Vessel fuel	Bait & supplies	Onboard communications	Vessel maintenance	Daily expense estimate
56±15	16±1	46±25	17±.025%	135±15	103±45	13±7	106±11	477±79

¹crew is paid as a percent of trip net.

seven species captured in the EFP trials, as well as the common thresher shark, *Alopias vulpinus* ($n=2$) and yellowfin tuna, *Thunnus albacares* ($n=1$). Swordfish comprised 58% of the catch during research trials and other marketable species made up an additional 37% of the experimental catch (95% marketable catch) (Table 2, Fig. 2b). Despite a more diverse assemblage of species caught during the research sets, standardized daily swordfish catch rates were similar for both research (mean=1.50 swordfish/8-h day) and EFP trials (mean=1.75 swordfish/8-h day). Incidental catch consisted of four blue sharks and a single northern

elephant seal that was released alive and in good condition (hook was left in place and the line was cut near the hook to reduce trailing gear). With the exception of swordfish, bigeye thresher sharks, escolar, and the northern elephant seal, all other species captured during the trials occurred on the shallowest hook (90–100 m depth).

Nocturnal research sets were also conducted from September 2014 through January 2017 on 30 different nights with an average soak time of 6.2 h/set. Sets were based on times and locations in which swordfish were present (based on concurrent daytime EFP and DGN fishing activity). Nocturnal

sets typically occurred at the same general location that a daytime EFP or research DSBG set had occurred. Sea-surface temperatures ranged from 16.5 to 25.0°C.

On average, 15.2 baited hooks were deployed per set at an average depth of 24 m (range 12–30 m) yielding a total of 2,997 hook soak hours. Eight swordfish were captured during nocturnal sets, which equated to approximately 9% of the total catch or 0.36 swordfish per 8-h set (Table 2, Fig. 2C). Other marketable species, including mako sharks and bigeye thresher sharks, comprised an additional 11% of the catch, resulting in a total marketable catch rate of ~20%.

The primary species encountered during nocturnal sets was the blue shark (76% of the catch), a species currently not marketed in the California fishery. A single California sea lion, *Zalophus californianus*, was also captured and released alive and alert following a brief (15 min) period on the line. Bait predation by California sea lions and other surface-oriented species (primarily pelagic sharks) occurred on 24% of baited hooks over the course of the study. For three of the sets, bait predation occurred on every hook that did not have a hooked blue shark or mako shark.

Tagging Data

Two blue sharks captured during nocturnal gear trials were opportunistically tagged to assess depth and temperature distribution within the study area. Mean night depth of the 136 cm and 205 cm FL blue sharks was 15.2 ± 16 m and 4.4 ± 4 m, respectively, with nearly all of the nocturnal records remaining consistently within the upper mixed layer. Daytime depth was more variable with routine bounce below the thermocline, with average daytime depths of 40.8 ± 8 m and 16.7 ± 30 m (Fig. 3).

Nocturnal trends of the two tagged blue sharks follow those of previous studies and suggest less variability at night, with 99.9% of the time spent above the average depth of the thermocline (~50 m; Fig. 3). When compared

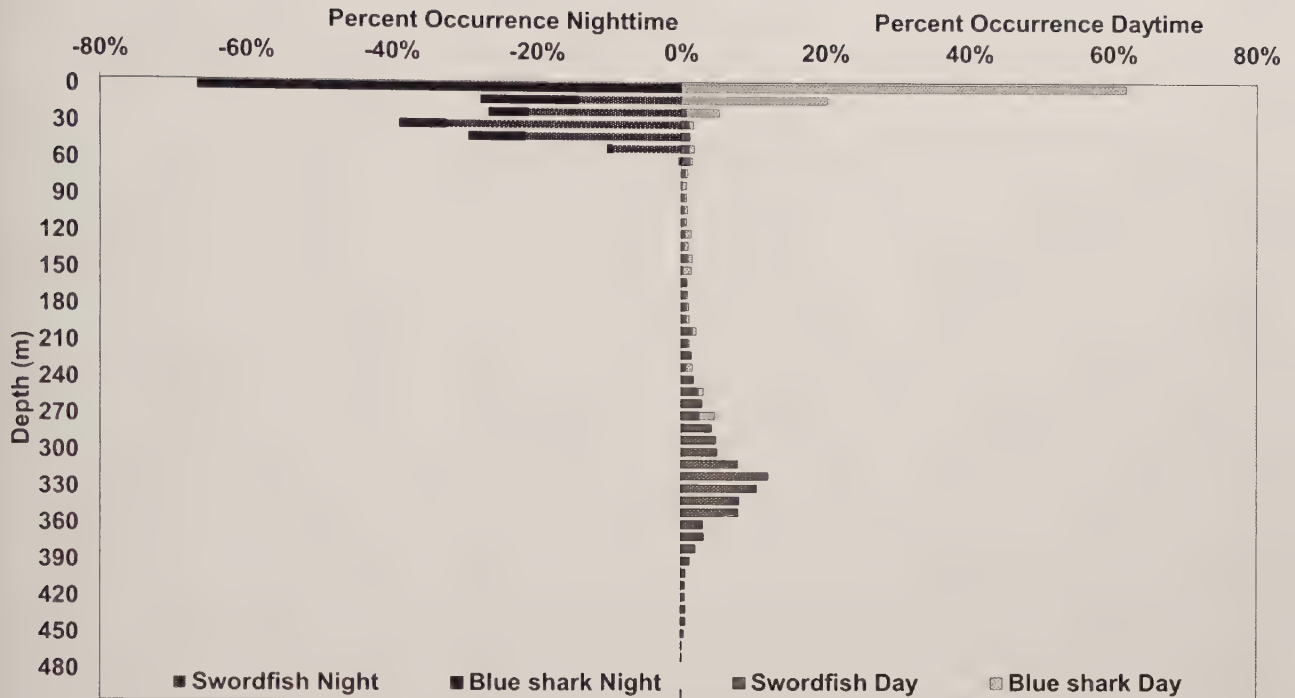


Figure 3.—Day and nighttime depth profiles summarized into 10-m bins from time series data collected during electronic tag deployments on two swordfish (130 and 152-cm fork length, FL) and two blue sharks (136 and 205-cm FL) off southern California in 2016–17.

to the two swordfish tagged in the same area (130 and 152 cm FL) and same time period, there was significant nocturnal overlap, with swordfish having an average night depth of 42.2 ± 9 m and 25.0 ± 8 m, respectively (Fig. 3). As previously shown, during the daylight hours swordfish remained predominantly below the thermocline, spending 97.1% of the day below the average depth of the thermocline (~ 50 m) (Fig. 3).

Discussion

This study focused on the testing of alternative fishing techniques for swordfish off Southern California from both cooperative and research vessel applications. Data corroborate previous findings and suggest that deep-setting during the day can result in high selectivity for swordfish off Southern California (Sepulveda et al., 2014). The EFP trials revealed similar swordfish catch rates and catch composition to that of simultaneous and previous DSBG research trials, while concur-

rent experiments comparing deep-day and shallow-night techniques within the same study area identified selectivity differences.

Given that the study area had high spatial overlap between swordfish and pelagic sharks (within the upper mixed layer at night), this study was not able to identify how nocturnal shallow-set operations can be modified to increase selectivity for swordfish. However, this work does provide support for the continued trial and use of deep-set daytime techniques with preliminary data suggesting that DSBG may provide west coast fishermen with a selective option for domestic swordfish harvest.

Set Times and Locations

PIER DSBG-EFP set locations align with historical set and catch data for both the DGN and harpoon fleets that continue to operate within the SCB (Hanan et al., 1993; Coan et al., 1998). Seasonal set locations and fleet movements followed the trends typical of the historic DGN fishery,

which follow frontal edges of both temperature and productivity (Hanan et al., 1993; Sepulveda et al., 2010). Cooperative fishermen set criteria varied extensively among participants, and typically entailed the combination of oceanographic conditions, historical fishing performance, ongoing fishing activity, and proximity to home port.

In September 2015, cooperative fishermen initiated deployments upon PIER DSBG-EFP authorization, which was approximately 2 months into the fishing season. In 2016, the EFP team was allowed to initiate deployments at their own volition, with initial sets performed in May. The first deployments coincided with the onset of summer conditions and the first sightings of swordfish by the commercial harpoon fleet (Fukushima⁴). During May and June of 2016, EFP participants exhibited a lull in DSBG activity as most of

⁴Fukushima, K. Cooperative swordfish fisherman, San Diego, Calif. Personal commun., Sept. 2016.

the vessels were more focused on the use of harpoon methods. DSBG catch and effort subsequently increased as harpoon catch and effort declined in July. Opportunistic harpooning of swordfish ensued throughout the duration of the trials by all EFP participants suggesting the complimentary nature of DSBG and harpoon operations in any future fishery.

Catch Composition

Swordfish comprised >80% of EFP catch, a selectivity value that is higher than both longline and DGN fisheries and lower than harpoon operations which typically have zero bycatch as they directly target swordfish swimming at the surface (Hanan et al., 1993; Coan et al., 1998; WCP-FC, 2014; PFMC, 2017). Other non-marketable species comprised <2% of the total EFP catch, consisting of only two species that are also incidentally caught in other fisheries within the SCB (Hanan et al., 1993; Obrien and Sunada, 1994). Catch composition over the two years of the EFP was found to be similar to concurrent and previous research trials spanning from 2011 to 2017 (Sepulveda et al., 2014; this study). The inter-annual consistency in catch composition is likely due to the relatively stable environmental conditions experienced at depth in the SCB (i.e., temperature, O₂ saturation), and the reduced tolerance to these conditions exhibited by most pelagic species (Levin, 2003; Bernal et al., 2009).

Selectivity for swordfish in the EFP trials was slightly higher than previous and concurrent research trials (Sepulveda et al., 2014). This difference is likely a product of the hook placement protocols, as the EFP terms and conditions did not mandate that cooperative fishermen deploy all three hooks. Because cooperative fishermen were primarily interested in the most profitable target (swordfish) and because the upper hooks had a greater tendency to tangle, >95% of the EFP deployments consisted of a single baited hook at the terminal end of the weighted vertical mainline. Similar trends have been reported in the Florida buoy fish-

ery (a shallow-set nocturnal operation), where fishermen typically use one hook when regulations allow two hooks per buoy (Burlew⁵).

Throughout the trials, the deepest (terminal) hook position has consistently produced the highest swordfish and bigeye thresher catch, while the upper-most hook position (~100 m) used to target opah has consistently yielded the highest non-swordfish catch to date (Sepulveda et al., 2014; this study). The DSBG research trials performed during this work employed a configuration that used all three of the baited hooks on each vertical mainline. If the EFP and research trials are compared using only the catch from the terminal hook, both groups had similar catch composition and marketable catch rates.

The BET shark was the second most common species caught in the PIER DSBG-EFP comprising ~16% of the total catch. It is a deep-dwelling species that shares a comparable diurnal depth distribution to that of swordfish (Nakano et al., 1997; Weng and Block, 2004; Sepulveda and Aalbers⁶). During the EFP trials it was observed that most of the BET captures occurred during sets near bathymetric features, a consideration that likely led to increased avoidance in Year 2 of the EFP. Of the 123 BET that were captured in the EFP, 24% were brought to market and the remainder were released alive.

To better assess DSBG impacts on the BET resource, tagging experiments were performed to assess post release disposition, with initial data suggesting high survivorship ($n=14$, ~90% survival rate; Sepulveda and Aalbers⁶). Bigeye thresher retention rates were dictated by the cooperative fishermen history of selling BET, hold space, and market dynamics. Early in the season or when swordfish catch rates were low, cooperative fishermen tended to retain more of the captured BET, while

they were almost all released when fishing for swordfish was good.

The two years of EFP deployments encompassed both strong El Niño Southern Oscillation (ENSO; Year 1) periods and ENSO-neutral conditions (Year 2). Despite differences in oceanographic conditions (i.e., sea surface temperatures, productivity), both years had similar catch composition, with the only notable difference being that Year 1 had a higher BET catch than Year 2. It is difficult to ascertain whether the increased BET catch was due to different environmental conditions, local shark abundance, or fisherman behavior (i.e., avoidance).

Catch rates

Although catch rates between different gear types are difficult to compare, swordfish catch during the PIER DSBG-EFP was within the range of daily catch rates for other California swordfish fisheries (i.e., DGN and harpoon). Swordfish landings from California harpoon vessels have historically fluctuated widely from 0.14 to 0.93 swordfish harvested per vessel day and are largely dependent upon regional oceanic conditions (Coan et al., 1998). Although California DGN vessels occasionally report catches of >30 swordfish in one night set, mean daily catch rates have been reported to range between 1 to 3 swordfish/set (Coan et al., 1998), a rate that is within the range of values observed in this study. Comparable catch rates are likely because both DSBG and DGN operate on a similar horizontal scale (1 nmi of net vs. 1 to 3 nmi footprint for DSBG) in an area where the swordfish resource is condensed into regional areas of productivity.

Similarly, the Florida shallow-set buoy fishery also operates in an area that is known for aggregating large numbers of swordfish (Kerstetter and Bayse, 2009). Although daily catch statistics for the Florida fishery are difficult to calculate from published literature, data obtained from an initial pilot study suggests catch rates to be similar to those of this study. In the Florida fishery, Kerstetter and

⁵Burlew, C. Commercial buoy fisherman, Deerfield, FL. Personal commun., 9/2015

⁶Sepulveda and Aalbers. Depth distribution and post release survivorship of bigeye thresher sharks. Manuscript on file at the Pflieger Institute of Environmental Research.

Bayse (2009) reported catches of ~202 swordfish/1,000 hooks while retained catch was on the order of ~145 swordfish/1,000 hooks (juvenile swordfish below 119-cm FL must be released). When compared to this study, the standardized catch estimate based on an 8 h soak period would be ~175 retained swordfish/1,000 hooks while the non-standardized estimate based on a 6.7 h soak would be ~147 swordfish/1,000 hooks.

As noted by Kerstetter and Bayse (2009), it is difficult to draw direct comparisons between catch rates on either shallow or deep-set buoy gear with longline catch rates, as they operate on different scales, deploy proportionally different numbers of hooks/set, have different soak times, and operate in different areas. However, in terms of number of swordfish per 1,000 hooks, both Florida shallow-set buoy gear and DSBG in this study exhibit a higher relative catch per unit effort (no. of fish/1,000 hooks) with lower overall volume captured compared to either the Atlantic or Hawaiian shallow-set longline fisheries. For example, results from this study suggest approximately 175 swordfish captured for every 1,000 hooks deployed for 8 h, while average catches in the Hawaii-based longline fishery range from 8–16 swordfish/1,000 hooks deployed (WCPFC, 2014).

Economic Analyses

Due to the low number of hooks deployed per day, economic viability has remained a concern for both managers and fishermen alike. Based on a cursory estimate of trip expenses, catch rates, and ex-vessel price, it was assumed that DSBG likely achieved economic viability during most of the EFP trips. This was also evidenced by fishermen continuing to use DSBG when they had access to other fisheries, including DGN. Based on an evaluation of price point, catch rate, and vessel operating costs, it was estimated that fishermen must land, on average, at least one swordfish per day in order to meet minimum trip expenses. This finding is similar to that

discussed by Coan et al. (1998) for the harpoon fishery.

Comparison of ex-vessel price among the different swordfish fisheries operating within the CA EEZ suggests that DSBG product is received at a comparable price-point to that of the traditional California harpoon fishery (Coan et al., 1998; PFMC, 2013) and nearly twice the ex-vessel price of DGN-caught swordfish (PFMC, 2017; Fukushima⁴). Although DSBG swordfish was consistently received at a higher price point than DGN product, DGN operations do also provide other products that can significantly contribute to trip revenue (Hanan et al., 1993). Returns from opah, several tuna species, and pelagic sharks can, at times, make up a significant component of the DGN revenue, a factor that makes direct profitability comparisons between DSBG and DGN more complex than just comparing swordfish alone. Further, given that most of the DGN caught swordfish in this study were landed in the late fall and early winter, the timing of the landings also makes landing and profitability comparisons difficult to interpret.

In the cursory estimation of trip expenses, vessel financing costs were not considered, as all individuals participating in the EFP owned their vessels outright. Other factors that may have artificially inflated revenue estimates include the standardization of catch statistics, variability in the number of travel days, and any fish transport costs that may have been paid by the fisherman. Standardization of the fishing day length was necessary because of the occasional short soak period (1–3 h) of some sets in both study years, a factor that further complicated catch and effort comparisons with other gears and studies.

The scaling of the results from this study to a larger DSBG fleet are also difficult to interpret, as market demand and price resilience are affected by many factors including fleet size, import volume, and market strength or resilience (Urbisci et al., 2016). Future work should focus on market demand and how it relates to fleet size and

profitability, factors that are needed for estimating optimal performance of any future fishery.

Sensitive Species Interaction

Although selective, DSBG trials had two observed interactions with northern elephant seals (one during the EFP and one during the research trials), a species that is abundant in the study area with a stock status that is not considered to be at risk (Lowry et al., 2014). The interactions confirmed the utility of the strike detection system in alerting fishermen to the presence of something on the line with both elephant seals (EFP and research vessel) being released promptly (<15 min) after the initial strike. Given the similar depth distribution and foraging behavior exhibited by swordfish and northern elephant seals it is unlikely that gear depth can be further altered to avoid future interactions (Le Boeuf et al., 1986; Maxwell et al., 2011). However, if deemed necessary, future work focused on northern elephant seal sensory biology may help identify possible methods to avoid future gear interactions. Similarly, ongoing work to develop electronic strike detection mechanisms may also reduce the amount of time non-targets spend on the line, a factor that has been shown to directly affect survivorship in many species (Gilman et al., 2006).

Research Trials

Experimental DSBG deployments were performed aboard the R/V *Malolo* to directly compare catch composition and selectivity between deep-daytime and shallow-nocturnal operations. Day and night sets were performed adjacent to ongoing EFP operations using similar set criterion (i.e., bathymetry, sea surface temperature, and productivity convergence). Nocturnal trials resulted in a catch that was largely dominated by elasmobranchs; with blue, mako, bigeye thresher, and smooth hammerhead sharks, *Sphyrna zygaena*, comprising ~90% of the catch. Blue and mako sharks have been shown to use the SCB as a rookery, with large numbers

of juveniles present during most of the swordfish fishing season (Tricas, 1979; Hanan et al., 1993; Sepulveda et al., 2004).

Similarly, both blue and mako sharks have been shown to display a mixed layer distribution at night with only the occasional excursion below the thermocline during the day (Holts and Bedford, 1990; Carey and Scharold, 1990; Sepulveda et al., 2004). Given that blue sharks were the most abundant (76.5%) non-marketable species encountered in the nocturnal trials, two individuals were electronically tagged to confirm previous movement studies and evaluate if interaction rates could be reduced through modifying nocturnal set depth. When compared to previous swordfish movement data (Sepulveda et al., 2010 and 2014) as well as the two tracks from swordfish tagged during this study, it was evident that both species exhibit significant overlap in nocturnal depth distribution (Fig. 3). Overlapping depth distribution coupled with the blue shark's abundance in the SCB likely led to the high interaction rate observed during the night sets (O'Brien and Sunada, 1994). These findings align with previous shallow-set longline experiments performed in the 1990's within the same study area which reported that >90% of the catch was composed of both blue and mako sharks (O'Brien and Sunada, 1994).

In addition to the high shark catch rates, bait predation was also a major factor contributing to the low swordfish catch at night. Shallow-set nocturnal deployments exhibited greater rates of bait predation (24%) relative to deep-set daytime trials (<5%), a result that supports the heightened competition for baited hooks in the upper mixed layer at night. During the nocturnal trials, it was assumed that juvenile blue sharks (<100 cm) were the primary source of bait predation. This was proposed due to characteristics of the bite marks, monofilament damage, and field observations of small blue sharks finning proximal to the deployment sites.

Conclusion

This work offers insight into the use of DSBG as a commercial fishing technique for harvesting west coast swordfish. Data support previous findings on DSBG off California and suggest high selectivity for swordfish and the live release of non-target catch. Given the decline in participation among California's west coast swordfish industry, this work provides a first step towards the development of sustainable techniques for harvesting a valuable domestic resource. Given that swordfish are capable of significant migrations and inter-annual changes in regional distribution, it is imperative that future work test the effectiveness of deep-setting throughout the range of the historic west coast fishery. Gear testing and exempted trials outside the SCB will help build a robust industry that can tolerate seasonal changes in abundance and further capitalize on this highly mobile domestic resource.

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A History of Research to Develop Guidance Systems to Divert Juvenile Salmonids, *Oncorhynchus* spp., from Turbines at Federal Hydroelectric Dams on the Mainstem Columbia and Snake Rivers, U.S.A.

JOHN G. WILLIAMS and MICHAEL H. GESSEL

Background

Pacific Northwest's Columbia River drains a watershed of 680,000 km², and historical flows in the lower river ranged from 1,400 to 28,300 m³/s, with the peak flows primarily resulting from glacial and snow melt (Williams and Tuttle, 1992). It also historically produced the largest number of Chinook salmon, *Oncorhynchus tshawytscha*, in the world (Netboy, 1980). Chapman (1986) estimated the peak combined adult return to the river of all salmonids, *Oncorhynchus* spp., in the late 1800's was approximately 8.9 M fish, comprised of 0.6 M spring, 2.5 M summer, and 1.3 M fall Chinook salmon; 2.6 M sockeye salmon, *O. nerka*; 0.6 M coho salmon, *O. kisutch*; 0.6 M steelhead, *O. mykiss*; and 0.7 M chum salmon, *O. keta*. Craig and Hacker (1938) detailed the tremendous decline in adult returns from the late 1800's into the

1930's and ascribed the majority of declines to overfishing, habitat destruction, and damming of tributaries for water withdrawal and small-scale hydropower.

The first mainstem dam (Fig. 1) on the Columbia River was completed at Rock Island, Wash., in 1933 and contained one fish ladder for upstream migrant adult salmon. This dam and the proposed dams to follow added another factor to consider when developing actions to limit the declines in fish stocks: the need to have adequate fish passage for the multitudes of fish runs that migrated up the river before turning into tributaries.

By the time Rock Island Dam was completed, the primary focus was on Bonneville Dam because of its planned location on the lower Columbia River (Fig. 1). Without effective fish passage measures in place at the time of its completion, it would potentially block and eliminate all salmon stocks and species in the river above it (Griffin, 1935).

Griffin (1935) noted that adult fish passage facilities would need to work immediately when the dam became operational because no time existed to conduct experiments to determine what type of facilities would work best.

At most, nearly all migratory salmon stocks in the river had only 4 or 5 adult-return year classes, so that even 1 or 2 yr without effective passage would seriously deplete stocks of fish. Thus, prior to construction of Bonneville Dam, tremendous efforts went into design of fish lifts, fish ladders, and collection channels with large amounts of flow. All were directed toward attracting returning adult salmon to the passage facilities that provided pathways to pass fish above the dam. Despite the concerns about fish passage at Bonneville Dam and designs of fish ladders to address them, nearly concurrent construction of Grand Coulee Dam (completed in 1941) on the upper Columbia River was begun, and due to its height (167 m), no fish facilities were considered for installation at the dam.

After completion of Bonneville Dam (Fig. 2) in 1938, studies immediately began to evaluate its effect on adult fish passage. In the adult ladders, 1 or 2 pools were modified to add a white board on the floor. When fish passed into the pool and over the board, personnel located above the pool could identify and count, by species, the fish passing up the ladder. The fish counts, rates of passage, and comparison of counts to upstream and downstream fisheries indicated that the ladders worked well (at least for salmon) (Holmes and Morton, 1939). Griffin (1935) speculated correctly that wing walls to divert downstream adult salmon and juvenile migrants to fish ladders and away from the power channel would not work. Several sluiceways installed near the spillway to attract and pass juvenile and adult fish downstream also failed and were subsequently abandoned.

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ABSTRACT—Eight large Federal hydro-power dams were constructed between the 1930's and 1970's on the mainstem lower Columbia and Snake Rivers, U.S.A. The dams included fishways that enabled effective upstream passage of adult salmonids to Snake River basin spawning areas, but they lacked any facilities for protection of juvenile salmonids migrating downstream to the ocean. Prior to completion of the dam complex, early studies on mortality of juvenile salmon passing through turbines suggested that Snake River salmon stocks

could not survive the cumulative mortalities to populations of fish that would have to pass downstream through turbines at all eight dams. This led to a more than 30-yr field effort conducted primarily by NOAA's National Marine Fisheries Service personnel to devise, test, and recommend for installation effective screening systems for turbine intakes at dams to decrease mortality of downstream migrating juvenile salmonids. This paper provides a history of the extensive research to accomplish this goal.

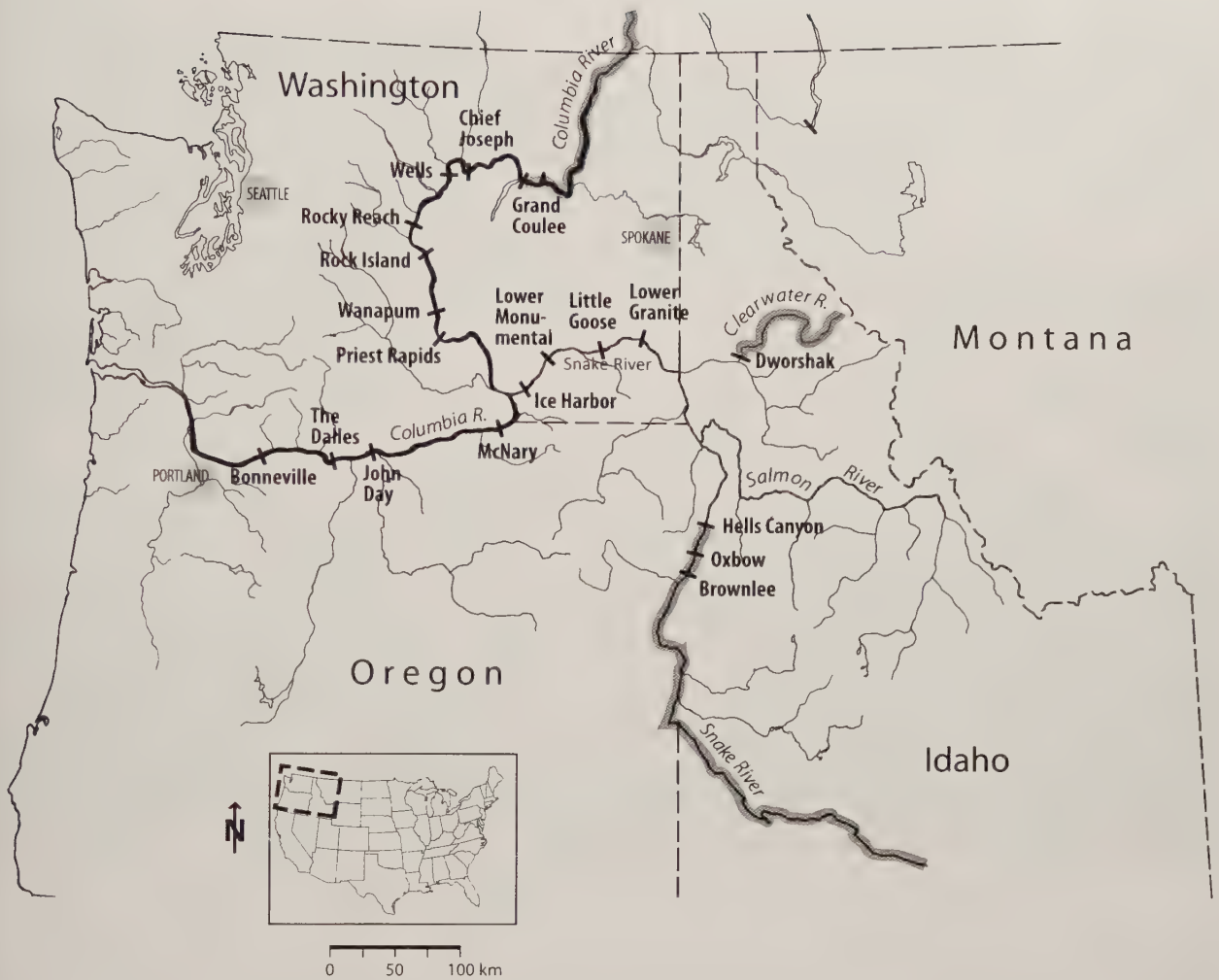


Figure 1.—Mainstem Columbia River Basin dams. Shaded areas indicate dams with no upstream fish passage facilities and extirpation of salmon runs. Chronological order of dam construction: 1933 – Rock Island; 1938 – Bonneville; 1941 – Grand Coulee; 1953 – McNary; 1955 – Chief Joseph; 1957 – The Dalles; 1958 – Brownlee; 1959 – Priest Rapids; 1961 – Ice Harbor, Rocky Reach, Oxbow; 1963 – Wanapum; 1967 – Hells Canyon, Wells; 1968 – John Day; 1969 – Lower Monumental; 1970 – Little Goose; 1974 – Dworshak; 1975 – Lower Granite; 1982 – Bonneville Dam Second Powerhouse.

While it was relatively easy to count adult fish moving upstream through the fish ladders at Bonneville Dam and relate passage to estimated river flows, the sheer size of Bonneville Dam and the size of the individual turbines made observing fish passing downstream through the dam nearly impossible, except for a small number of juveniles collected in surface collection traps (Gauley et al., 1958). Lower Columbia River flow during the peaks of the downstream migration generally ranged from 4,000–5,000 m³/s in low-

flow years and up to 10,000–14,000 m³/s in high-flow years (Raymond, 1979).

The Bonneville powerhouse is 182 m wide and contains 10 Kaplan¹ turbine units, each about 15 m wide and which can pass up to about 375 m³/s of flow. The spillway is another 365 m wide. Thus, the total linear distance at the dam through which downstream migrants can pass is so large that sam-

¹Mention of trade names or commercial firms does not imply endorsement by the National Marine Fisheries Service, NOAA.

pling the area was not initially attempted. Because a large proportion of spill was expected to occur during periods of peak migration, it was expected that large numbers of salmonid smolts (size range of 75–165 mm fork length) would pass through the spillway (with unknown effects) during periods when discharge exceeded powerhouse capacity (Griffen, 1935).

Without direct observations of downstream migrating fish, studies of the effects of turbines and spill on downstream juvenile salmon were begun



Figure 2.—Aerial view of Bonneville Dam First Powerhouse, spillways, and fish ladders near completion.

using large numbers of juvenile Chinook salmon taken from the Bonneville Hatchery. Fins were clipped and fish were released through hoses into the turbines and spillways (treatments) and tailrace (control) over several years beginning in 1938 (Holmes²). Adult returns to the hatchery from the different groups were compared in subsequent years.

Notes from the work indicated a bias in return rates may have existed due to different combinations of fin clips used to mark juvenile fish. Adults of juveniles with pectoral clips returned at lower rates than some other fin-clip

combinations. Nonetheless, in general, based on adult returns, juvenile fish released into turbines had mortality rates 5–6 times higher than juvenile fish that passed downstream through spillways.

At the end of WWII, with the U.S. economy improving, plans for many additional dams in the Columbia River basin were made. Often, justification for new dams relied more on political support for construction than on a direct need for additional power production (Dietrich, 1995). Five additional dams were constructed on the mainstem Columbia and Snake Rivers in the 1950's, eight in the 1960's, two in the 1970's, and an additional powerhouse was added to Bonneville Dam in the early 1980's (Fig. 1).

Of the dams built in the 1950's, Chief Joseph did not have fish pas-

sage facilities because construction of Grand Coulee Dam 15 yr earlier, just 82 km upstream, had blocked all fish passage. Brownlee Dam on the Snake River also had no upstream passage facilities; thus, none were included at Hells Canyon and Oxbow dams when they were constructed. This led to extinction of native runs above Hells Canyon on the Snake River.

In the 1950's and 1960's, considerable research was conducted on upstream passage through ladders at experimental facilities located within laboratories at Bonneville Dam and those results led to improvements in adult passage facilities at dams already in place as well as development of new configurations subsequently installed as new dams were built (Collins et al., 1963; Gauley and Thompson, 1963; Monk et al., 1989).

²Holmes, H. B. 1952. Loss of salmon fingerlings in passing Bonneville Dam as determined by marking experiments. Unpubl. in-house rep., 62 p. U.S. Dep. Inter., Fish Wildl. Serv, Bur. Commer. Fish. Portland, Oreg. [on file at NOAA, NWFSC Library, Seattle.]

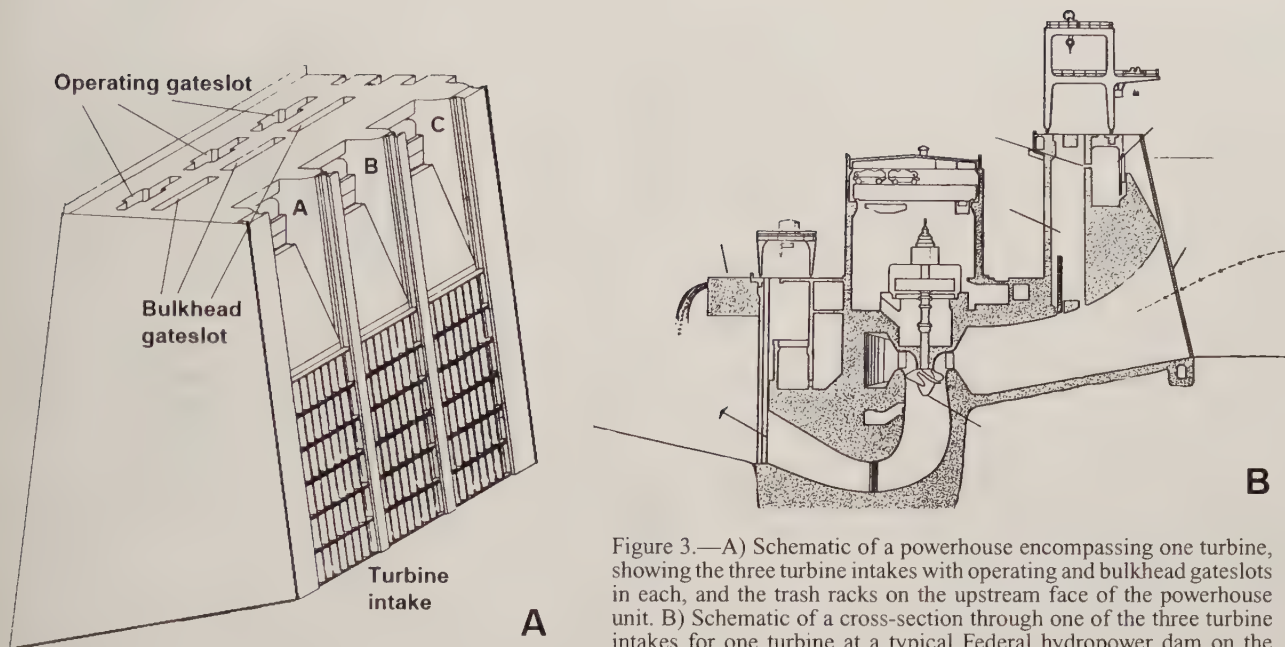


Figure 3.—A) Schematic of a powerhouse encompassing one turbine, showing the three turbine intakes with operating and bulkhead gateslots in each, and the trash racks on the upstream face of the powerhouse unit. B) Schematic of a cross-section through one of the three turbine intakes for one turbine at a typical Federal hydropower dam on the lower Snake and Columbia Rivers.

After the completion of McNary Dam in the early 1950's, a more rigorous evaluation was made to estimate the effects of passage through turbines and spill on juvenile salmonids (Schoeneman et al., 1961). Results of this research were similar to the earlier Bonneville Dam studies—juvenile fish passing through spillways survived at about 98%; whereas, fish that passed through turbines survived at about 89%.

These survival study results provided great concern about how well salmon stocks in the upper Columbia and Snake River basins would survive once all planned dams in the lower mainstem rivers were constructed. Dams constructed after Bonneville Dam had greater numbers of turbine units; thus, a greater percentage of river discharge would go through the turbines. Discharge was envisioned to occur through spillways only under the highest flows at most new dams. With at least eight mainstem dams that juvenile fish would need to pass, direct passage survival through turbines as fish passed eight dams was expected to lead to less than 40% $[(0.89)^8 = 0.39]$ survival of juveniles migrating from the Snake River to below Bonneville Dam.

In the late 1950's, the Bureau of Commercial Fisheries (BCF) founded a field station in Weiser, Idaho, with the charge to begin studying the effects that Brownlee Dam on the Snake River would have on passage of juvenile and adult salmon and steelhead above and below the dam. When the first studies indicated deleterious effects would occur, a broader mandate was given in 1961 by Interior Secretary Stuart Udall. He originated a Fish Passage Program (FPP) to investigate problems of fish passage at high-head dams and develop solutions for the proposed dams in the mainstem of the lower Snake River (Trefethen, 1968).

Other BCF investigations on adult and juvenile fish passage at dams that were already underway were rolled into this larger FPP mandate. A subpart of these investigations was research to alleviate mortality of juvenile salmonids that entered turbine intakes at dams. While the research began in earnest in the early 1960's, earlier studies in the 1940's and 1950's provided some of the initial information needed on which to plan studies on fish movement in the river and into turbines. Here, we provide the history

of more than 30 yr of research begun in the 1960's that led to the development of screening and bypass systems for juvenile salmonids at Federal Columbia River hydropower dams.

Dam Structure

To understand how the research to develop guidance systems evolved requires an understanding of the basic structure and configuration of turbine intakes at the powerhouses of Federal dams on the lower Columbia and Snake Rivers; all of which were designed, built, and are operated by the U.S. Army Corps of Engineers (USACE). Each powerhouse on the lower Snake River has six turbine units. On the lower Columbia River, the number of turbine units varies among powerhouses: 8 at Bonneville Dam Second Powerhouse, 10 at Bonneville Dam First (the original) Powerhouse, 22 at The Dalles Dam, 16 at John Day Dam, and 14 at McNary Dam.

All powerhouses have vertical Kaplan turbines. The size of individual turbine bays at all dams is relatively the same; however, turbine output varies depending on the decade of turbine installation, the hydraulic head of the

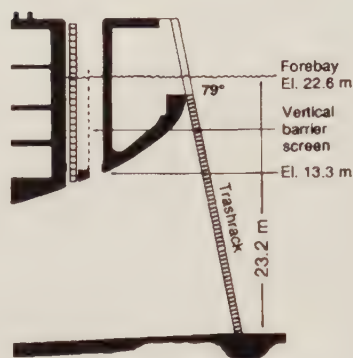
dam, and power production when operated within 1% of peak efficiency.

The flow through each turbine generally ranges between 280 and 595 m³/s when operated within 1% of peak efficiency. Newer dams generally have turbines with higher discharge capabilities. Due to the size of the turbines, structural limitations require that at the upstream face of the dam each individual turbine requires three turbine intake entrances through which water flows toward the turbine (Fig. 3a.) Water flows through trash racks with horizontal spaces of about ¼ m width that limit large objects from entering the turbines.

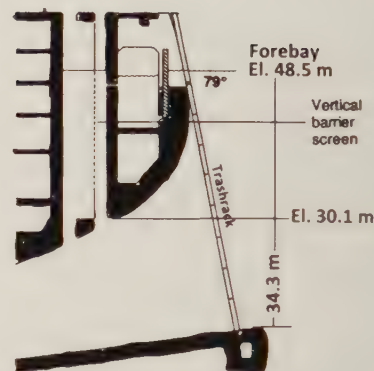
While all entrances have the same dimension, because of the flow pulled through the turbine by spinning blades, the proportion of flow into the three entrances varies. About 33% of the flow goes into the middle entrance (B: intake in figure), while (looking downstream), the entrance to the left (A: intake in figure) passes about 36% of the flow and the one on the right about 31%. Since the entrances all have the same cross-sectional area, the velocity of water into the three turbine intakes also varies in direct proportion to the percentage of flow into the intake. Water flowing through the three turbine intakes converges into a single mass downstream of the three operating gateslots. It then flows through the wicket gates and over the turbine blades (sometimes called the runner) and discharges into the tailrace.

Powerhouses at Columbia River dams are not solid masses of concrete. Above each of the three turbine intakes is a large gatewell with two rectangular openings at the deck level and at the turbine ceiling intake level (Fig. 3b.). These openings create two vertical slots that in plan-view are about 6 m wide x 2 m deep. In the upstream slot (called the "bulkhead gateslot" in this paper) channel indents exist on the long axis into which it is possible to place concrete bulkheads to block flow into the turbine. The downstream slot provides the space for an operating gate and is referred in this paper as the "operating gateslot."

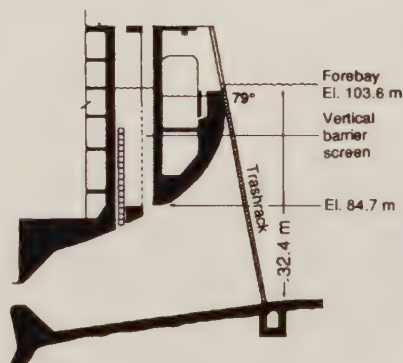
Bonneville (first powerhouse)



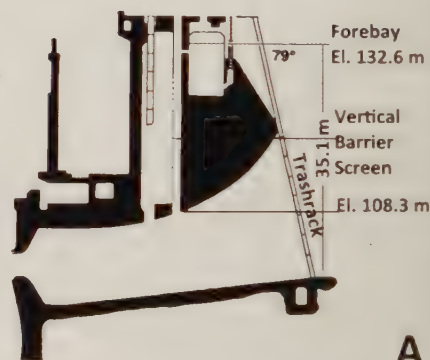
The Dalles



McNary



Ice Harbor



A

Figure 4.—A) Schematic cross-sections through the four powerhouses constructed with an ice and trash sluiceway across the forebay side (earliest powerhouses of the Federal hydropower dams on the lower Snake and Columbia Rivers). B) (facing page) Schematic cross-sections through the five powerhouses constructed without an ice and trash sluiceway across the forebay side (most recent powerhouses of the Federal hydropower dams on the lower Snake and Columbia Rivers).

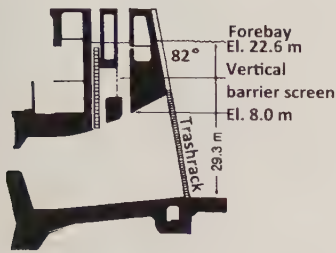
At most dams each operating gateslot of each turbine intake contains a hydraulically controlled, or cabled operating gate that in case of an emergency can be lowered quickly to the bottom of the intake to stop water flow into the turbine. If no barriers exist in the bulkhead gateslot, water enters the gatewell to the level (or nearly that) of the forebay. When the turbine is operating and neither gateslot has a barrier, a small percentage of water entering the turbine intake passes up into the gatewell via the bulkhead gateslot and

exits the gatewell via the operating gateslot.

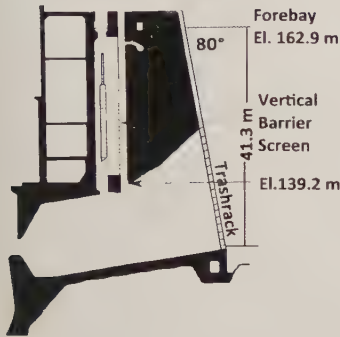
The size of the structural masses of concrete at the bottom and top of the gatewell vary between powerhouses (Fig. 4.) The vertical height of the gatewell and porosity of vertical barrier screens (discussed below) influences the amount of water flowing into the gatewell when the turbine is operating.

In addition to different sized gatewells, the profile of the turbine intake ceilings at the nine Federal hydropow-

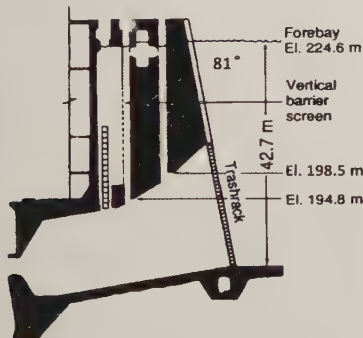
Bonneville (Second Powerhouse)



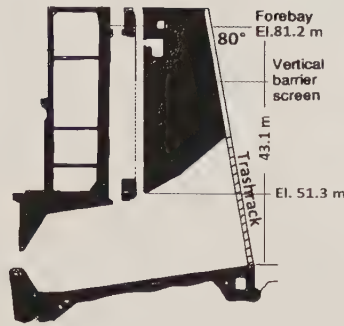
Lower Monumental



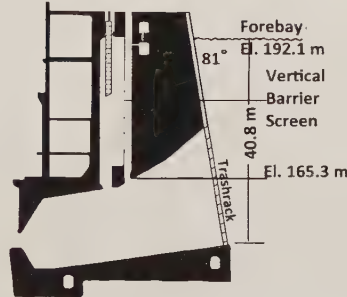
Lower Granite



John Day



Little Goose



B

tion of juvenile salmon entering the forebay based on data collected from nets fished across the powerhouse from the surface to about 17 m, in 3 m increments (Burner³). While the results had variability and indicated that juvenile salmonids could be captured at any depth, they indicated that fish were more often near the surface. Studies conducted concurrently with traps in the auxiliary water systems between 1946 and 1953 determined that migrants tended to pass in greatest numbers at dusk and dawn (Gauley et al., 1958).

An auxiliary observation from the early years of collecting juveniles at Bonneville Dam was that during periods of high river discharge (about early April to late June) woody debris and small salmon were entrapped in the top of the gatewells of operating turbine units. Since little water flowed into gatewells compared to the volume flowing into turbine intakes, this observation suggested that fish possibly entered the gatewell while trying to swim toward the surface and avoid the bulk of water flowing deeper into the turbine unit. This led to directed research in 1959 to quantify the numbers of smolts in gatewells at Bonneville Dam (Long⁴). At Bonneville Dam in one 5-day period, nearly 6,500 fish were removed from one gatewell. The research was replicated at McNary Dam in 1961. Fish were removed from gatewells in test units with a large dipnet (Bentley and Raymond, 1968), sorted by species, and counted. Over 9,500 fish were removed from gatewells at McNary Dam in a 13-day period. Research-

³Burner, C. J. 1949. Vertical distribution of downstream migrating Chinook salmon fingerlings in the Bonneville forebay, with a note upon the rate of migration. Unpubl. in-house rep. U.S. Dep. Inter., Fish Wildl. Serv, Bur. Commer. Fish. Portland, Oreg. [on file at University of Washington Allen Library (SH222.W32 B87).]

⁴Long, C. W. 1964. Occurrence of fingerling salmonids in turbine intake gatewells. Rep. No. 50, In Collins, G. B., and C. H. Elling (Editors), Fish-passage research program review of progress 1964, 7 p. Volume IV, Rep. of the Accelerated Fish-Passage Research Program to the Bur. Commer. Fish., Seattle. [avail. at https://www.nwfsc.noaa.gov/assets/4/6692_10242016_132412_Long.1964-FPR-IV-50.pdf].

and Bonneville Second Powerhouse dams from the late 1960's to 1980's have no ice and trash sluiceways above the turbine intakes; they have flat and relatively steep faces on the upstream side of the dams, and relatively flat turbine intake ceilings that intercept the forebay reservoir at a water depth of approximately 10 m below the forebay level.

Phase 1: Early Research on Juvenile Fish at Dams, 1946–68

Research in 1947–48 at Bonneville Dam determined the vertical distribu-

er dams on the lower Snake and Columbia Rivers has two general shapes (Fig. 4). The powerhouses constructed at Bonneville First Powerhouse, The Dalles, McNary, and Ice Harbor dams in the 1930's to early 1960's have ice and trash sluiceways built into the upstream side of the powerhouse and the ceilings of the turbine intakes curve upward from the bulkhead gateslot to a point relatively close to the forebay water level and just below the ice and trash sluiceway. The powerhouses constructed at Lower Granite, Little Goose, Lower Monumental, John Day,

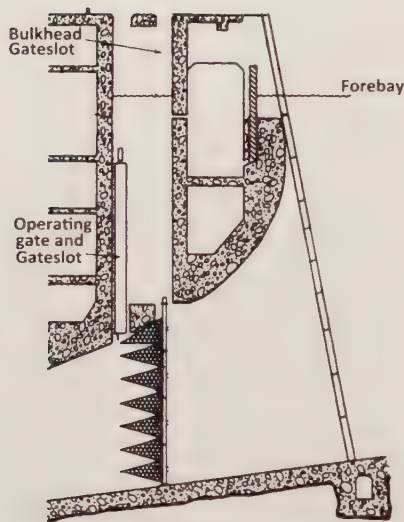


Figure 5.—Schematic of a typical fyke-net configuration to determine vertical distribution of fish entering a turbine intake. In early years three columns of nets were generally used to cover the entire intake area. In later years, only the center column contained nets. Various net dimensions were used in some years to better define the vertical distribution that was potentially intercepted by various screen lengths. Nets were generally placed in the bulkhead gateslot, but were sometimes placed in the operating gateslot, particularly when testing extended-length screens.

ers concluded that since fish naturally moved into gatewells from the turbine intakes, efforts should begin to find means to increase the number of fish entering gatewells, determine a means to keep them in the gatewells so that they would not pass back into the turbine intake, and develop a method to divert fish from the gatewells to a non-turbine route past the dam.

Also in this decade, research on screening methods to divert juvenile migrant fish was conducted at the Tracy Pumping Station on California's Sacramento River (Bates and Vinsonhaler, 1957). Results of this research indicated that horizontal traveling screens did not attain high diversion percentages but they suggested the possibility that screens with a traveling mesh could divert fish from a turbine intake.

In 1960 and 1961, Long (1968) used fyke nets placed vertically within turbine intakes (Fig. 5) to study the temporal and vertical distribution of fish in turbine intakes at McNary and The Dalles dams. Recoveries of fish indicated that if the majority of salmonids were in the upper one-third of the intake, they would most likely pass through turbines near the hub so that improving passage conditions near the hub might increase turbine survival, and that the use of deflection and bypass techniques near ceiling intakes might deflect a high percentage of fish entering the turbine intake. He also confirmed earlier findings from sluiceway studies at Bonneville Dam that most juveniles passed into the turbines between dusk and dawn. Related to the studies to determine vertical distribution of fish at McNary Dam, additional research was conducted to see if lights in the forebay at the dam would change the vertical distribution of fish passing into the turbine intake (Long⁵; Fields⁶). The research by Long⁵ indicated they did not. Another behavioral study evaluated an electrical curtain as a means to possibly move fish away from deleterious passage routes (Pugh et al., 1970), but results from the 1962 research indicated that electrical screens did not have much feasibility to guide salmonids in water velocities greater than 0.3 m/s. In addition to the fact that river velocities often exceeded this rate, it seemed infeasible to develop an electric array in the large forebay expanses at dams on the Columbia or Snake Rivers.

⁵Long, C. W. 1964. Effect of lighted conditions at a surface bypass on the vertical distribution of fingerling salmonids in a turbine intake (summary). Rep. No. 51, In Collins, G. B., and C. H. Elling (Editors), Fish-passage research program review of progress 1964, 4 p. Volume IV, Rep. of the Accelerated Fish-Passage Research Program to the Bur. Commer. Fish., Seattle. [avail. at https://www.nwfsc.noaa.gov/assets/4/6690_10242016_142536_Long.1964-FPR-IV-51.pdf].

⁶Fields, P. E. 1966. Final report on migrant salmon light guiding studies (contr. rep. D.A.-45-108 CIVENG-63-29) at Columbia River dams, 267 p. Rep. to Fisheries Engineering Research Program, U.S. Army Engineer Division, North Pacific Corps of Engineers, Portland, Oreg.

Several years later, Monan et al. (1969) found that juvenile Chinook and coho salmon migrated in higher proportions in the outer one-third of the river than in the middle one-third, and generally the majority were in the upper one-third of the water column. As with early studies at Bonneville Dam, fish were detected from the surface to the bottom of the river. More importantly related to potential juvenile bypasses, the fish were also mixed with a large amount of debris. The authors concluded that to collect most juvenile salmonids arriving at a dam would require straining nearly the entire water mass, and it would require a method capable of coping with large quantities of debris.

By 1964, the general consensus among BCF researchers was that they would, in the short-term, follow a dual path on addressing passage of fish through turbines at dams. The first was to determine if it were possible to improve survival through turbines by altering operations, and if successful, determine if altered operations were feasible when needs of power were considered. The second was to determine the feasibility of using screens, behavioral devices, or a combination of both that would attract or divert fish into the gatewells as fish passed into the turbine intakes, all the while dealing with the debris load in the river during the migration period.

Based on the earlier vertical distribution research at The Dalles and McNary Dams (Long, 1968), in 1964, the first proposal was made to use diversion screens within turbine intakes to divert fish into gatewells at dams (Long⁷). Four different potential means to increase the percentage of juveniles entering the gatewell were proposed: 1) raise the operating gate to increase the flow into the gatewell

⁷Long, C. W. 1964. Increasing the percentage of fingerlings entering intake gatewells—a proposal. Rep. No. 56, In Collins, G. B., and C. H. Elling (Editors), Fish-passage research program review of progress 1964, 3 p. Volume IV, Rep. of the Accelerated Fish-Passage Research Program to the U.S. Bur. Commer. Fish., Seattle. [avail. at https://www.nwfsc.noaa.gov/assets/4/6691_10242016_150033_Long.1964-FPR-IV-56.pdf].

through the bulkhead gateslot, 2) lower the operating gate into the turbine intake to block the path of fish passing near the turbine intake ceiling, 3) insert a screen down the bulkhead gateslot that would extend into the turbine intake, and 4) place a screen on the front of the trash rack to divert fish higher into the water column.

To obtain basic information for the design of a suitable fish guiding device, the BCF constructed a model at the Fisheries-Engineering Research Laboratory at Bonneville Dam that simulated a segment of a turbine intake and gateway. Equipment tested in this structure included baffles, expanded metal plates to modify flows and fish behavior, and a diversion screen (VanDerwalker, 1970; Marquette and Long, 1971).

Between 1962 and 1968, BCF also conducted field research at Bonneville Dam (Long and Marquette⁸) and at Ice Harbor Dam (Long et al.⁹) to determine the effect of turbine passage on juvenile fish and whether it looked feasible to manipulate turbines to alter survival. Results from the 1968 Ice Harbor Dam studies indicated significant mortality from predation for fingerlings that ended up in the back-roll area of the tailrace after they had passed through turbines (Long et al.⁹). Thus, BCF researchers concluded that even if turbines were made sufficiently safe, the best approach to protect fish would be a system to bypass fish around turbines in order to avoid high predation on fish exiting turbines. Therefore, all efforts turned toward de-

veloping systems to divert fish away from turbine intakes into gateways at dams.

Consensus of researchers was to try a diversion screen. Long and Krcma (1969) developed an initial proposal to install and test a "juvenile salmonid bypass system" at Ice Harbor Dam. They envisioned putting self-cleaning traveling screens down the bulkhead gateslots that would protrude into the flow within the turbine intake and divert juveniles into gateways (Fig. 3). The rationale for a self-cleaning screen was based on the large amount of debris that entered the reservoir at Ice Harbor Dam and built up along the face of the dam. Although the dam had an ice and trash sluiceway to facilitate moving ice and trash to the tailrace of the dam, the debris nonetheless had already shown a propensity to move into gateways. Near the top of each gateway, a submerged orifice would connect to the ice and trash sluiceway which discharged through a chute into the tailrace of the dam.

The orifice placement was based on research at Ice Harbor Dam in 1965 where the optimum placement of an elliptical 56 cm x 46 cm orifice was submerged 1.5 m deep and located in the corner of a gateway (Liscom, 1971), plus additional research on prototype 15.2 cm diameter orifices installed in the center intakes of Turbine Units 5, 8, and 11 at McNary Dam and tested in 1968 (Bentley and Raymond, 1969).

Efficiency of the orifices to pass fish out of gateways was called orifice passage efficiency (OPE). It was initially determined by comparing the number of fish removed from the gateways with and without orifices. A hinged dip basket (Bentley and Raymond, 1968), sometimes called a butterfly dip basket because with the two sides open the basket looked somewhat like it had butterfly wings, was used to remove fish from the gateways.

At McNary Dam, the combined OPE of all salmonids was generally greater than 80%. Based on these results, prior to the 1969 migration season a single 15.2 cm diameter orifice

was installed 0.5 m from the north corner in the remaining gateways for the 14 turbine units at the McNary Dam and in all of the gateways for all operating turbine intakes at Ice Harbor Dam. The research also led to installation of 15.2 cm diameter orifices at John Day (1969), Lower Monumental (1969), and Little Goose (1971) dams (Smith and Farr, 1975). The newer dams did not have integral ice and trash sluiceways, so the orifices emptied into conduits mined within the dams that channeled water to a release site in the tailrace of the dam.

With the exception of the initial preliminary orifice research (Bentley and Raymond, 1969; Liscom, 1971), most concepts in the juvenile bypass proposal were untested. Thus, the Long and Krcma (1969) proposal contained basic questions that the research would need to address:

1) Would the traveling screens guide a sufficient proportion of the population entering the turbine intake? [Guidance rate—subsequently called "fish guidance efficiency" (FGE)],

2) Were screens structurally safe to put into the intake and would they work well mechanically for the duration of the juvenile migration? [Mechanical reliability],

3) Would traveling screens impinge fish and if impinged, would they come off the rotating screen as the screen face reached the entrance to the gateway? [Effect of screens on fish descaling]. In the 1960's, BCF researchers had devised a methodology and a standard to assess if a salmon was considered "descaled." The result was that a fish missing scales on 10% of its body was considered descaled. The methodology to determine descaling was detailed in a report by Basham et al. (1982). In this paper, all references to descaled fish or descaling rates of fish relied on this same methodology,

4) What percentage of fish would survive? [Survival of fish in gateways],

5) Would fish diverted into the gateway readily find the submerged orifices and pass into the ice and trash sluiceway? (OPE), and

⁸Long, C. W., and W. M. Marquette. 1964. Program of research on fingerling passage problems associated with Kaplan turbines, 1962-64. Rep. No. 43, In Collins, G. B., and C. H. Eling (Editors), Fish-passage research program review of progress 1964, 22 p. Volume IV, Rep. of the Accelerated Fish-Passage Research Program to the U.S. Bur. Commer. Fish., Seattle. [avail. at https://www.nwfsc.noaa.gov/assets/11/6697_10242016_124820_Long.and.Marquette.1964-FPR-IV-43.pdf]

⁹Long, C. W., R. F. Krcma, and F. J. Ossiannder. 1968. Research on fingerling mortality in Kaplan turbines—1968. Fingerling Passage Program, Prog. Rep. Bur. Commer. Fish., Seattle, 7 p. [avail. at https://www.nwfsc.noaa.gov/assets/26/7335_07232012_125411_Long.et.al.1968.pdf].

6) Would predation increase for fish concentrated by a bypass system and released into the tailrace? [Survival of fish in tailrace].

Phase 2: Initial Juvenile Bypass System Implementation and Evaluation, 1969–70

The physical structure of the intake screens was based on earlier research to develop horizontal traveling screens to divert juvenile salmonids in irrigation canals (Bates et al., 1970; Bates and Vanderwalker, 1970). Wire mesh on the outside of the screen captured debris and as the mesh rotated to the back side of the screen, the water current washed it off. For turbine intakes, as the rotating screen reached the top of the frame adjacent to the gatewell, the direction of water velocity trended toward entering the gatewell and impinging fish could move off the screen or were washed off as the screen rotated to the back side of the frame.

Before testing a prototype screen at Ice Harbor Dam, tests were conducted in a scale model of an Ice Harbor Dam turbine intake using different variants of wire-mesh porosity on screens. The tests determined how flow disruption created by the guiding device set at a 45° angle to the perpendicular frame affected hatchery fish released into the model. The screens with the least porosity diverted the most fish. For field tests, screens designed for turbine intakes were inserted vertically into the bulkhead slot, the screen was lowered into the turbine intake, pendant cables were pulled to raise the screen to a 45° angle, and a hydraulic pump rotated cogged wheels which rotated the mesh around the screen (Farr¹⁰). Each screen was quite large, with dimensions of approximately 6 m wide and 6 m in length (Fig. 6).

The initial test of a prototype submersible traveling screen (STS) oc-



Figure 6.—Original submersible traveling screen (STS) used at Ice Harbor Dam and shown with the screen extended. While later variations of standard STS were tested with different screen materials and porosity, the overall dimensions of standard STS remained the same.

curred at Ice Harbor Dam in 1969. The primary objective of this study was to conduct mechanical tests with the device installed in an operating turbine to examine performance and to pinpoint potential problem areas. The testing was initially set for a 2 month window between early April and early June when juvenile spring–summer Chinook salmon and steelhead smolts migrated to the ocean from the Snake River. Late delivery and mechanical problems limited spring testing in 1969 to only a couple of days (Marquette et al.¹¹).

Biological evaluation of the screen only occurred for two tests late in May. The effectiveness of the STS was based on a comparison of the number

of fish removed by a hinged dip basket from the gatewells of two turbine intakes of Turbine Unit 3: one with the prototype STS (Gatewell B) and one without (Gatewell A). The tests were relative because without a barrier screen in the gatewell inserted between the bulkhead and operating gateslots, most of the fish diverted into the bulkhead slot swam out of the operating gateslot and back into the turbine intake. No obvious differences in the numbers of fish removed from gatewells in turbine intakes with or without an operating STS were found.

In the fall, the STS was operated only to evaluate mechanical reliability. The screen had a mechanical failure after 29 days. Additional tests were also conducted at McNary Dam in 1969 on the ability of fish to exit gatewells through 15.2 cm diameter orifices (Marquette et al.¹¹). The tests indicated that a darkened gatewell that had a bright light on the downstream side of the orifice caused the least amount of retention of fish in the gatewell. Reten-

¹¹Marquette, W. M., F. J. Osslander, R. Duncan, C. W. Long, and R. F. Krema. 1970. Research on gatewell-sluice method of bypassing downstream migrant fish around low-head dams. Rep. to U.S. Army Corps Eng., Walla Walla District by U.S. Bur. Commer. Fish., Seattle, 32 p. [avail. at http://www.nwfsc.noaa.gov/assets/26/7146_07022012_135038_Marquette_et.al.1970.pdf].

¹⁰Farr, W. E. 1973. Traveling screens for turbine intakes of hydroelectric dams. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Northwest Fish. Cent., Seattle, unpubl. rep., 20 p. [avail. at https://www.nwfsc.noaa.gov/assets/26/7325_07232012_110859_Farr.1973.pdf].

tion within the gatewell over a 24 h period, however, was approximately 50% for Chinook juveniles. Little apparent mortality or descaling occurred on fish transiting the sluiceway after passing through orifices. Due to high flow conditions, no measure of survival of fish entering the tailrace was possible.

In 1970, the prototype STS was again tested at Ice Harbor Dam as were OPE tests (Long et al.¹²). More than three times as many juvenile Chinook salmon were dipnetted from the gatewell with the STS than the one without, but the numbers of steelhead were about the same. As in 1969, no barrier screen was in place within the gatewell to trap fish in the bulkhead gateslot. The greatest concern was that the percentage of fish remaining in the gatewell was much higher at Ice Harbor Dam than was found at McNary Dam the year before. Researchers concluded that a barrier screen was needed in the gatewell between the operating and bulkhead gateslots to contain fish in a confined area so that they would more readily have contact with the orifice. As for the lack of diversion of steelhead by the prototype screen, it was decided that in order to determine potential causes, research tests would require the inclusion of fyke nets below the STS to provide the ability to compare the number of fish passing above the screen with the number passing below.

The construction and operation of mainstem dams on the lower Snake and Columbia Rivers in the 1960's and early 1970's led to a substantial decline of salmon and steelhead populations from the Snake River basin (Raymond, 1979). Thus, in addition to research to develop screening systems for turbines as a potential means to decrease mortality to downstream migrant smolts, research began on the feasibility of collecting salmonid smolts at dams and then transporting them past down-

stream reservoirs and dams to avoid the cumulative mortality of migrants passing through multiple turbines in the hydropower system.

The first transportation studies were conducted during 1968–70 at Ice Harbor Dam. Juveniles were collected from gatewells by a dipnet, marked, and a portion were transported by truck to a release site below Bonneville Dam while the remainder were released at Ice Harbor Dam to continue their migration (Ebel et al., 1973).

Results from these initial studies indicated that marked and transported fish returned at higher rates than marked fish migrating downstream from Ice Harbor Dam. Because of these positive results, interest in collecting and transporting fish increased. Thus, over the next decade, the bulk of the juvenile bypass system research was focused on dams where transportation was considered a viable option: Little Goose and Lower Granite Dams on the lower Snake River and McNary Dam on the lower Columbia River.

**Phase 3: Development and
Evaluation of
Initial STS and Orifice Bypass
Installations in Turbine
Intakes at Lower
Snake River Dams, 1971–79**

In 1971, BCF became the National Marine Fisheries Service (NMFS) under the National Oceanic and Atmospheric Administration (NOAA). All of the staff and field stations that conducted the earlier research remained the same and continued the ongoing efforts to address passage problems at dams. Evaluations of STS and orifice installations were moved upstream to Little Goose Dam with its completion in 1971 (Ebel et al.¹³). Rather than

one orifice per gatewell as was initially installed at McNary Dam, at Little Goose Dam two 15.2 cm diameter orifices were installed in each gatewell and each was bell-mouthed (larger diameter in the gatewell end constricting to a 15.2 cm diameter at the exit into the mined channel).

Three prototype STS were tested in Turbine Unit 2. This allowed screening all three intakes of one turbine unit, thus limiting the potential bias of fish moving between screened and unscreened intakes within the same operating turbine. Considerable mechanical failures of the STS during the spring migration period limited the number of feasible tests. For tests, in the center turbine intake (2B), a frame with 12 fyke nets attached was placed below the STS and a net (closure net) attached to the top of the backside of the STS frame (Fig. 7). The fyke-net-frame nets were designed to capture fish diverted below the STS and the closure net to capture fish diverted above the STS (but not into the bulkhead gateslot). These latter fish were expected to include volitional migrants as well fish impinged on the STS mesh that were then dislodged as the mesh rotated to the backside of the screen.

To confine diverted fish into the bulkhead gateslots of the three turbine intakes, a vertical barrier screen (VBS) (Fig. 8) was installed between concrete masses at the top and bottom of the gatewell that separated the bulkhead and operating gateslots in each turbine intake (Fig. 3b). This configuration led to the design and construction of a new dip basket that would more efficiently remove fish diverted into bulkhead gateslots (Swan et al., 1979). For turbine units without the test STS, only one gatewell in one turbine intake had an installed VBS.

With VBS and STS installed in all turbine intakes of one turbine unit, and a new dipbasket to remove fish more efficiently from gatewells, the first formal procedures to measure the effectiveness of the STS to divert fish out of turbine intakes were developed. To conduct a test, the turbine unit was turned off and orifices in the three in-

¹²Long, C. W., R. F. Krcma, W. M. Marquette, and R. Duncan. 1970. Further research on a fingerling bypass for low-head dams (1970). U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Seattle, unpubl. rep., 23 p. [avail. at http://www.nwfsc.noaa.gov/assets/26/7336_07232012_130019_Long.et.al.1970.pdf].

¹³Ebel, W. J., H. L. Raymond, C. W. Long, W. M. Marquette, R. F. Krcma, and D. Park. 1971. Progress report on fish-protective facilities at Little Goose Dam and summaries of other studies relating to the various measures taken by the Corps of Engineers to reduce losses of salmon and steelhead in the Columbia and Snake Rivers. Report to U.S. Army Corps of Engineers, Walla Walla District by NOAA, Natl. Mar. Fish. Serv., Seattle, 40 p. [avail. at http://www.nwfsc.noaa.gov/assets/26/6607_08042010_082952_Ebel.et.al.1971a-rev.pdf].

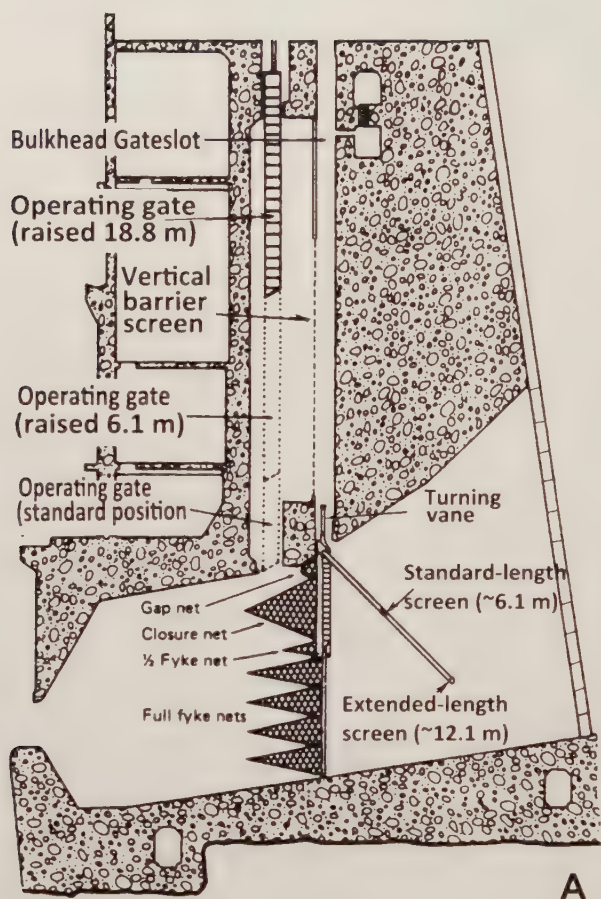


Figure 7.—A) Schematic of a turbine intake showing general configuration of a deployed standard or extended-length screen in a normal position. The identified turning vane at top of screen was not used in early years of testing. The fyke-net configuration was used for tests of standard screens. For nearly all extended screen tests, a fyke-net frame was inserted in the downstream operating gateslot. Operating gate shown in the 3 most common test configurations. B) Photograph of an STS with fyke nets behind the screen and on a portion of the fyke-net frame attached to the bottom of the STS ready to lower into the bulkhead gateslot.

takes closed. The STS with fyke-net frame attached was lowered into the center turbine intake and the dipbasket was used to remove all fish from the gatewell. The unit was then put into operation for a specified time.

To terminate a test, the turbine unit was shut off, a dipbasket removed all fish from the gatewell of the center intake, and the STS with fyke-net frame were then removed from the bulkhead gateslot. The fish captured in the fyke nets and in the closure net were counted by species, and the sum of these totals was added to the total number of fish by species removed from the

gatewell. For each species and each test fish guidance efficiency (FGE) estimates were made. The FGE equaled the number of fish in the gatewell divided by the total number removed from the gatewell plus those captured in all nets.

In two tests conducted in late April, the FGE ranged from 81% to 97% for yearling Chinook salmon and steelhead, respectively (Farr¹⁰). However, during the 1971 tests, periods of time existed when a relatively high number of fish removed from gatewells were descaled (greater than 10% of body scales missing). No obvious causes

were found although it seemed possible that some fish were already descaled on arrival at the dam or became so after passing debris on the trash racks.

From the beginning of the field season, it was clear that fish accumulated in gatewells with and without VBS. Special screens to crowd fish toward the orifices were employed to speed removal of fish from gatewells, but retention of fish in the gatewells was still unacceptably high. In mid-May clear plastic tubes that converted the bell-mouthed orifices to the non-tapered type used at McNary Dam

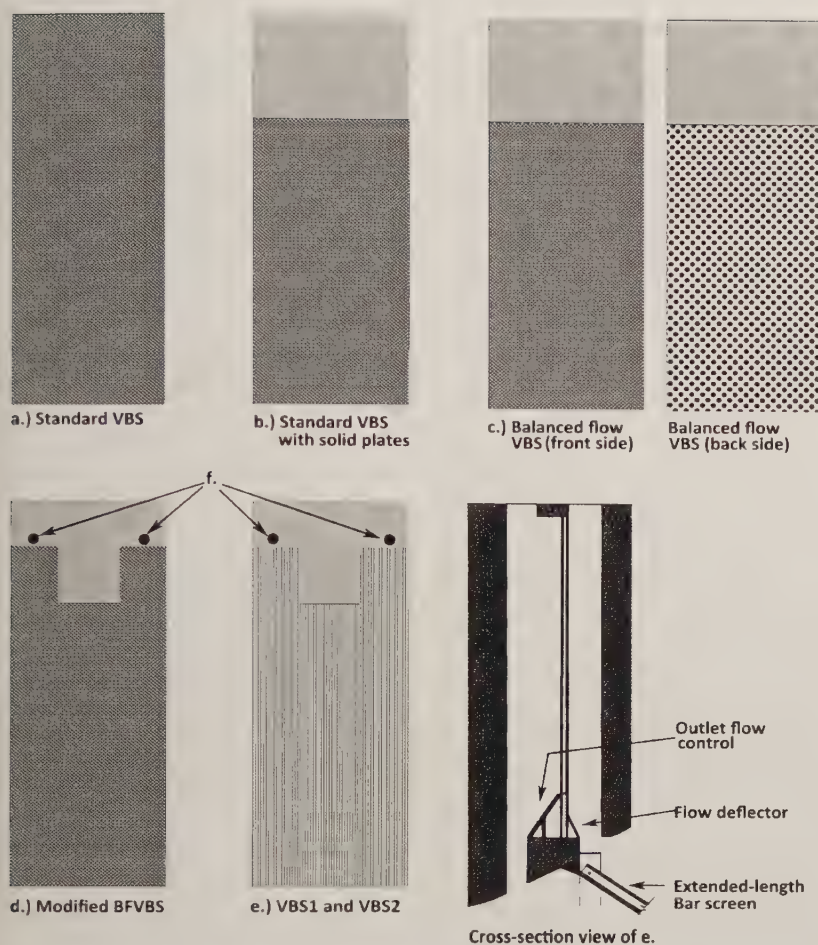


Figure 8.—Schematic of vertical barrier screen (VBS) configurations (not to scale) showing the side fish encounter when entering a bulkhead gateslot. Screens evolved over time to improve gatewell conditions. The original screens (a) had only a polyester mesh (1971–72). All VBS (b–e) had a solid panel added to the top beginning in 1973 (the size of panels varied depending on the gatewell hydraulics at the dam at which they were installed). Flow through mesh panels was balanced with the addition of perforated plate added to the downstream side of the VBS (c–e) beginning in 1982. The perforation pattern was based on gatewell hydraulics and varied among dams. These screens were termed balanced flow vertical barrier screens (BFVBS). Alteration of the solid panels on BFVBS (d) to provide additional screened flow in vicinity of orifices (f) installed through the upstream gatewell wall was first tested in 1984. Only half of the upper panel was modified if only one operating orifice existed in the gatewell. This new configuration was termed the modified-BFVBS. When testing extended length screens in 1994, VBS with upstream mesh replaced with wedge-wire screen were tested (e). [Note]: the bottom of the VBS (e) also had a deflector on the upstream side to smooth flow entering the gatewell, and a plate on the downstream side to control the overall flow into and out of the gatewell.

were inserted in gatewells with VBS. Each insert was equipped with a mercury vapor lamp so that when lit, the lamps provided illumination to the orifice exit. This change simulated the condition that worked so successfully at McNary Dam in 1969 (Marquette

et al.¹¹). Changing the orifices from a bell-mouthed configuration into a straight-tube configuration (Smith and Farr, 1975) improved OPE; however, when the two conditions that provided the best conditions for orifice passage at McNary Dam were tested at Little

Goose Dam, 22–41% of fish were still in the gatewell after 24 h; a value considerably less than satisfactory.

Because of the high FGE observed during the two 1971 STS tests, the STS related research for the next several years was directed toward the development of an STS that would reliably operate throughout a field season, specifically in the areas of the drive system, the drive chain, and different types of roller bearing material, while at the same time not injuring smolts or delaying their downstream passage. Further, because of concerns about mortality to fish captured in fyke nets and because the tests in 1971 had indicated high guidance, the majority of the tests in 1972 and 1973 did not use fyke nets underneath the STS. Instead, run-of-the-river migrants were captured either through gatewell dipping or purse seining in the forebay, marked by freeze brand, and then released through a hose (Fig. 9) into the test turbines for evaluation. While this approach eliminated the fyke-net mortality, it only provided a relative estimate of fish guidance.

During the 1972 field season, the three test STS at Little Goose Dam operated during the major period of downstream migration which was considerably longer than in 1971, but collectively only 60% of the time (Ebel et al.¹⁴). Repeat of 1971 OPE tests with aluminum tubing inserts found that continued accumulations of fish in the gatewell occurred, presumably as a result from delays in fish passage through the submerged orifices and due, in part at least, to excessive turbulence in the gatewells. When turbines were shut down, turbulence in gatewells ceased and fish movement through orifices increased.

¹⁴Ebel, W. J., H. L. Raymond, C. W. Long, W. M. Marquette, R. F. Krema, and D. Park. 1973. Evaluation of fish protective facilities at Little Goose Dam and review of other studies relating to protection of juvenile salmonids in Columbia and Snake Rivers, 1972. Progress report to U.S. Army Corps of Engineers, Walla Walla District by NOAA, Natl. Mar. Fish. Serv., Seattle, 52 p. [avail. at http://www.nwfsc.noaa.gov/assets/26/6610_08042010_084030_Ebel.et.al.1973c-rev.pdf].

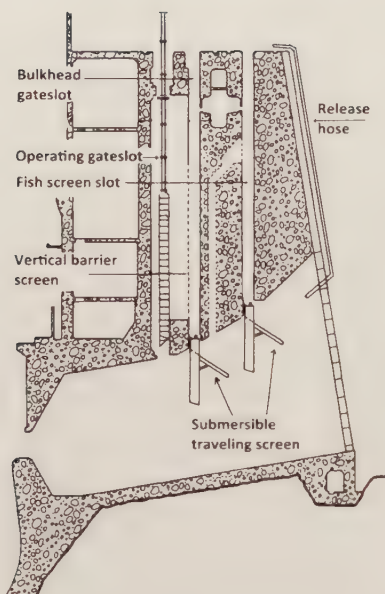


Figure 9.—Schematic of Lower Granite Dam turbine intake configuration. Release hoses were used at Little Goose and Lower Granite dams from 1972 to 1979 to evaluate FGE of STS.

Tests were conducted with a modified VBS to see if it would reduce gatewell turbulence and increase fish passage. The porosity of the VBS in gatewell 1B was decreased in two test series to change the flow pattern in the gatewell. In one set of tests, plywood sheets were attached to the upper 9.7 m and lower 4.8 m of screen, which left approximately 11 m of uncovered screen between the panels. For a second set of tests, only the upper 9.7 m of screen was covered. In the tests where both upper and lower portions of the screen were covered, it decreased flow into the gatewell by about one-half compared to conditions with an unmodified VBS. Turbulence in the gatewells was reduced, but the reduction of water inflow apparently resulted in decreased percentages of fish entering the gatewell.

When solid plates were installed only at the top of the VBS, flow entering the gatewell was not significantly reduced, while at the water surface gatewell turbulence was essentially eliminated along with an increased

percentage of fish exiting through the orifices. Fish observed at the water surface of the gatewell were well distributed and swimming with much less effort than in adjacent control gatewells with unmodified VBS. Researchers recommended modifying all of the VBS at Little Goose Dam. A test of smaller STS mesh was also tried to see if it would decrease descaling, but the smaller mesh had decreased porosity which increased flow and turbulence in the gatewell. No change in descaling was seen.

In 1973, nine STS were installed at Little Goose Dam in the three operating turbine units (Ebel et al.¹⁵). While the screens initially worked without undue problems, high rates of descaling on fish in gatewells led to removal of six of the nine screens by 11 May. The remaining three STS were used to evaluate possible causes for the high descaling observed. Results of evaluations indicated that in gatewells with STS, an average of 13.9% of Chinook salmon smolts were descaled compared to 4.1% in gatewells without STS. Tests of different STS configurations indicated that the higher rates of descaling were related to the screen-mesh size of STS and to the level of turbine unit operation; high loads (high turbine flow) caused increased gatewell turbulence and descaling.

Further, 1973 was a low-flow year, and the estimated survival of smolts migrating from Little Goose Dam to The Dalles Dam was quite low (Raymond, 1979). Based on the low survival of migrants in 1973 and the earlier results that indicated fish collected and transported from Ice Harbor Dam to a release site below Bonneville Dam had adult returns that were 50–300% greater than fish that migrated through the river, efforts were no longer directed at developing effective release sites

of fish guided away from turbines. Instead, plans were made to transport all fish guided into gatewells from Snake River dams to a release site below Bonneville Dam.

In 1974, the STS guidance research at Little Goose Dam was focused on finding a screen mesh size in combination with or without a 48% porosity plate behind the mesh that would provide the highest guidance with acceptably low levels of descaling (Ebel et al.¹⁶). Field tests included combinations of different screen-mesh size and perforated plate behind the STS screen, lights placed in turbine intakes to potentially attract fish closer to the intake ceiling as a means to increase guidance and decrease descaling, and variable turbine loads.

The lowest descaling rates occurred with regular mesh backed by a 48% perforated porosity plate and at peak turbine efficiency. The same porosity plate when used with intermediate mesh (less strands of wire per surface area that created a higher surface velocity condition) led to higher descaling rates. The turbine intake water velocity increased by approximately 40% when the turbine was operated at full load. This led to lower recovery of fish in the gatewell and also higher rates of descaling. Lights on the turbine intake ceiling had no measurable effect on the percentage of fish recovered in the gatewell or the rate of descaling under full turbine load, but did lead to an approximately 10% increase in recovery under peak efficiency load.

Even with the release hose attached so that fish exited downstream of the trash racks, recovery of Chinook salmon released through the hose only ranged from approximately 50% under full turbine load to 65% under peak turbine efficiency load. Steelhead des-

¹⁵Ebel, W. J., R. F. Krcma, and H. L. Raymond. 1973. Evaluation of fish protective facilities at Little Goose Dam and review of other studies relating to protection of juvenile salmonids in Columbia & Snake Rivers, 1973. Progress Report to U.S. Army Corps of Engineers, Walla Walla District by NOAA, Natl. Mar. Fish. Serv., Seattle, 52 p. [avail. at http://www.nwfsc.noaa.gov/assets/26/6611_08042010_084301_Ebel.et.al.1973-rev.pdf].

¹⁶Ebel, W. J., R. F. Krcma, D. Park, H. L. Raymond, E. Slatick, E. M. Dawley, and G. A. Swan. 1974. Evaluation of fish protective facilities at Little Goose Dam and review of other studies relating to protection of juvenile salmonids in the Columbia and Snake Rivers, 1974. Progress report to U.S. Army Corps of Engineers, Walla Walla District by NOAA, Natl. Mar. Fish. Serv., Seattle, 50 p. [avail. at http://www.nwfsc.noaa.gov/assets/26/6612_08042010_084732_Ebel.et.al.1974b-rev.pdf].

caling rates were uniformly lower than for Chinook salmon while recovery rates in the gatewell were uniformly higher.

Although the research at Little Goose Dam from 1971–74 did not provide proven designs for fully operational STS systems, results appeared promising. In addition to the transportation results from Ice Harbor Dam, the early results from research at Little Goose Dam also indicated that juvenile fish transported in trucks from the dam to a release site below Bonneville Dam produced higher adult returns compared to fish that migrated through the dams in the hydropower system (Ebel, 1980). The combined results of these transportation studies and the lower survival of juvenile salmonid smolts that migrated in low-flow years increased the urgency to develop and install complete screening systems at Little Goose Dam and influenced the design of Lower Granite Dam.

Lower Granite Dam was somewhat different than at the other lower Snake River dams. To potentially avoid tying up bulkhead gateslots with an STS, a fish screen slot (FSS) was designed and built into the dam (Fig. 9.) It was envisioned to hold a STS, intercept juveniles close to the entrance to the turbine intake ceiling, and guide fish up the slot where they could pass through an orifice. The FSS had several potentially beneficial characteristics: 1) the cross sectional area of water entering the turbine intake is larger and the water velocity lower than at the entrance to the bulkhead gateslot, 2) the angle of flow approaching STS deployed in the FSS is more acute potentially lessening the chance of descaling, and 3) the ceiling of the intake on the upstream side of the FSS is cut off horizontally allowing a larger opening into the FSS than in the bulkhead gateslot with installed STS.

Similar to Little Goose Dam, the gatewell at Lower Granite Dam had a VBS with the upper 11 m containing a solid plate (Fig. 8b). In all turbine intakes, both the upstream wall of the bulkhead gateslot and the downstream wall of the FSS had two, 20.3

cm diameter orifices installed and they were modifiable to a 15.2 cm diameter orifice—the standard size installed at other dams. Water exiting the orifices flowed into a gallery constructed within the powerhouse structure. Although only one turbine unit was in operation at Lower Granite Dam in 1975, the majority of research related to development of STS was moved upstream to it from Little Goose Dam (Park et al.¹⁷). The basic design and mechanical operation of the STS had evolved to what was considered a workable piece of gear (Farr¹⁸), but additional research was considered necessary to fine-tune the STS to make it both “fish friendly” and relatively maintenance free.

Research in 1975 tested STS in both the FFS and bulkhead gateslot. All screens had 48% porosity plates, two of them had regular mesh, and one screen had intermediate mesh. All tests were conducted at full turbine load. Run-of-river fish were captured from gatewells, marked, and released through hoses back into the turbine intake into an area about 1.5 m downstream from the trash rack and 1.5–2.0 m above the STS (Fig. 9.) Marked fish recovered from gatewells by dipnet provided relative recovery rates for different tests and fish were observed to determine fish condition.

The positive benefit of perforated plate backing observed at Little Goose Dam was confirmed at Lower Granite Dam in 1975. Overall average percent descaling for salmon in the bulkhead gateslots was 6.4%, which was much reduced from the 21% rate recorded in previous years when there was no

perforated plate backing behind the screen. Nonetheless, the 6.4% descaling rate in the bulkhead slot was still considered unacceptable in the long term. Of the two mesh sizes, descaling was lower with the intermediate mesh compared to the regular.

The descaling rate of juvenile Chinook salmon and steelhead recovered from the FSS averaged about 20%, nearly three times higher than the descaling rate of fish recovered from the bulkhead gateslot. The high descaling rate of fish in the FSS was thought to be related to the fixed 45° angle of the STS and how the flow intercepted the screen face. Recommendations were made to construct a new STS that could operate at variable angles.

Additional guidance tests were conducted in fall 1975 using pre-smolt Coho salmon released through hoses in order to test two turbine loads, two mesh sizes for the screens, and plates inside the screen with two different porosities. Further, the water was clear enough to take videos of fish behavior in the area of the screens, and lights were placed at the entrance of the FSS to determine if illumination might increase guidance. It quickly became apparent that the hatchery Coho salmon did not behave the same as natural migrants nor have the same rate of descaling. They did provide some relative differences in descaling and led to the conclusion that the 33% porosity plate with the intermediate mesh size was the best combination to try in the future. The FSS continued to show large increases in descaling compared to the bulkhead gateslot. Design was in progress for screens adjustable to variable angles.

While the guidance work was not very successful, evaluation of the lighted, 20.3 cm diameter orifices indicated that few salmonid juveniles remained in the gatewell after 24 h of operation. Results were compared to passage through two 15.2 cm diameter orifices and the smaller orifices were again considered unacceptable because about twice as many fingerlings stayed in the gatewell compared to residual counts when two 20.3 cm diameter

¹⁷Park, D., E. M. Dawley, R. F. Krcma, C. W. Long, E. Slatick, J. R. Smith, and G. A. Swan. 1976. Evaluation of fish protective facilities at Little Goose Dam and Lower Granite Dams and review of other studies relating to protection of juvenile salmonids in the Columbia and Snake Rivers, 1975. Report to U.S. Army Corps of Engineers, Walla Walla District by NOAA, Natl. Mar. Fish. Serv., Seattle, 50 p. [avail. at http://www.nwfsc.noaa.gov/assets/26/6808_08092011_115116_Park.et.al.1976-rev.pdf].

¹⁸Farr, W. E. 1976. Status of traveling screen development - 1976. NOAA, Natl. Mar. Fish. Serv., Northwest Alaska Sci. Cent., Seattle, 11 p. [avail. at http://www.nwfsc.noaa.gov/assets/26/7326_07232012_111319_Farr.1976.pdf].

orifices were open. Exploratory tests indicated there was no preference for egress through the south vs. the north orifice. Further testing was deemed necessary to determine if a single 20.3 cm diameter orifice would be adequate for optimum passage.

In 1976, studies continued at Lower Granite Dam to evaluate standard and three new, variable-angle STS adjustable from 45° to 65° in 5° increments and operated in either the FSS or the bulkhead slot (Park et al.¹⁹). The STS had two types of mesh and porosity: regular mesh backed by 48% porosity plates and an intermediate mesh backed by 33% porosity plates. Tests of both screen porosities and varying screen angles in the FFS and bulkhead gateslots found that the highest recovery rate of fish released from hoses occurred in the bulkhead slot with intermediate mesh size and 33% porosity plates. The lowest recovery rate occurred in FSS with regular mesh and 48% porosity plate.

The new variable-angle screens had a number of mechanical problems that limited their use at times. Under the best conditions, the descaling rate on Chinook was only 3% compared to the 6% in 1975; however, steelhead descaling remained at about 6%. When the screen was set at angles of 50° or higher in the FSS, descaling of fish removed from the gateway was similar to those recovered from the bulkhead gateslot. The lowest descaling rates tested under all conditions generally occurred with the 33% porosity plate behind the intermediate traveling mesh. Because of mechanical problems with the new adjustable screens, it was recommended that another year of testing was needed and that screens with lights should be tested.

In 1976, further testing at Lower Granite Dam of new lighted 20.3 cm orifices confirmed the results obtained in 1975—that the larger orifice worked much better than the originally installed 15.2 cm orifices at Little Goose Dam. Few fish remained in gatewells after 24 h with the former compared to 20–30% with the latter. Continued problems existed with descaling of fish collected at Little Goose Dam and much of it was thought related to fish delayed in gatewells due to inadequate orifice size. New studies were proposed to test different sized orifices in the downstream side of the gateway (operating gate area), including mechanical controls to open and close them, prior to the spring 1977 outmigration.

In 1977, all three operating turbine units at Lower Granite Dam were screened, the first dam in the river to achieve this. Studies were planned to monitor the prolonged operation of STS equipped with intermediate mesh and 33% porosity plates in all bulkhead slots of Units 2 and 3 and to evaluate the condition of juvenile smolts within the bulkhead slots. Research was also directed at evaluation of the adjustable-angle traveling screens for guidance and descaling effects on natural migrant Chinook salmon smolts in relationship to optimum screen angle, percent open-area perforated plate, lighting condition, and to determine a preferred location for operation in either the bulkhead gateslot or the FSS (Park et al.²⁰).

Similar to research results in 1976, even with new adjustable STS, screens placed in the bulkhead gateslots recovered more fish with lower descaling rates than screens placed in the FSS. An angle of 60° in combination 33% porosity screens provided conditions in which fish had the lowest rates of

descaling and the highest rates of recovery. Descaling rates in 1977 were much higher than in earlier years and the increase was attributed to the historic low flows and variable turbine operation (Williams and Matthews, 1995), not to the equipment tested. As in previous years, measures of fish guidance were based on recovery of fish released through hoses that had been inserted into the turbine intake.

New test orifices were not installed at Little Goose Dam as proposed because very low Snake and Columbia River discharge in the winter and early spring of 1977 required operation of all turbine units at Little Goose Dam for power generation; thus, delaying installation of the new orifices until mid-June—at which time smolts were no longer available to test the system. An evaluation of the system was rescheduled for 1978.

By the start of the spring juvenile salmonid migration in 1978, STS had been installed in all six of the now operating turbine units at Lower Granite Dam (Park et al.²¹). The effectiveness of the STS was determined by periodically sampling juveniles from gatewells and measuring levels of descaling. The screens were presumed operating satisfactorily based on average descaling rates of 3% and 5% for steelhead and Chinook salmon, respectively, and because large numbers of fish were collected for transportation.

Evaluation of orifices at Little Goose Dam continued in 1978. The top two panels of the VBS were removed so that fish guided into the bulkhead slot would have access to the test orifices installed in the downstream wall of the gateway (in the slot with the operating gate) (Park et al.²⁰). Marked juvenile Chinook salmon and steelhead were released simultaneously into the bulkhead gateslot and along

¹⁹Park, D., J. R. Smith, E. Slatick, G. A. Swan, E. M. Dawley, and G. M. Matthews. 1977. Evaluation of fish protective facilities at Little Goose and Lower Granite Dams and review of nitrogen studies relating to protection of juvenile salmonids in the Columbia and Snake Rivers, 1976. Report to U.S. Army Corps of Engineers, Walla Walla District by NOAA, Natl. Mar. Fish. Serv., Seattle, 47 p. [avail. at https://www.nwfsc.noaa.gov/assets/26/7222_07092012_102141_Park.et.al.1977-rev.pdf].

²⁰Park, D., J. R. Smith, E. Slatick, G. M. Matthews, L. R. Basham, and G. A. Swan. 1978. Evaluation of fish protective facilities at Little Goose and Lower Granite Dams and review mass transportation activities 1977. Report to U.S. Army Corps of Engineers, Walla Walla District by NOAA, Natl. Mar. Fish. Serv., Seattle, 60 p. [avail. at http://www.nwfsc.noaa.gov/assets/26/6809_08092011_115936_Park.et.al.1978-rev.pdf].

²¹Park, D., J. R. Smith, G. M. Matthews, L. R. Basham, G. A. Swan, G. T. McCabe, T. R. Ruehle, J. R. Harmon, and B. H. Monk. 1979. Transportation activities and related research at Lower Granite, Little Goose, and McNary Dams 1978. Report to U.S. Army Corps of Engineers, Walla Walla District by NOAA, Natl. Mar. Fish. Serv., Seattle, 65 p. [avail. at http://www.nwfsc.noaa.gov/assets/26/6810_08092011_120249_Park.et.al.1979-rev.pdf].

with natural-river migrants recovered 24 h later after passing through one of the orifice/light combinations tested. Test combinations included north and south 20.3 cm diameter orifices that were lighted or dark, north and south 25.4 cm diameter orifices that were lighted or dark, a single north 25.4 cm diameter orifice that was lighted, and a single south 30.5 cm diameter orifice.

During the tests, a special effort was made to maintain operating STS with a uniform full-turbine generating load of 155 megawatts. The test results, while not providing clear evidence for an optimum orifice arrangement did show that two lighted, 20.3 cm diameter orifices passed fish better than a single 25.3 cm or 30.4 cm diameter orifice. However, recovery rates of fish passing through orifices were low. This indicated that many fish passing over the top of the VBS passed down through the operating gateslot and back into the turbine rather than through the orifices. Further studies to test orifices drilled into the downstream wall of the gatewell were abandoned.

Measurements of flow direction within surface waters of gatewells indicated that different gatewells for turbine intakes A, B, or C (as noted earlier, each turbine intake has a different level of flow) had different flow directions. Because of continuing high descaling with the 15.2 cm diameter orifices, it was recommended to replace them with both a north and south 30.4 cm diameter orifice in each turbine intake gatewell.

In 1979, the recovery rate of Chinook salmon and steelhead smolts captured, marked, and released in the forebay was only an estimated 31% and 50%, respectively, at Lower Granite Dam (Smith et al.²²). This was a much lower proportion than the assumed FGE if the STS and orifices had worked correctly. Further, since

the fish descaling rate was low and similar to 1978, it was assumed that the low collection rate was a result of the large level of debris in the forebay of the dam (Williams and Matthews, 1995, discuss debris issues). Some of the debris impinged on the trash racks in front of turbines and presumably altered the flow of water which, in turn, decreased STS effectiveness (Park et al.²¹). At Little Goose Dam, the old orifice system had been dismantled, but a new system was not yet installed. Fish collected by dipnet from gatewells had much higher descaling levels than fish collected at Lower Granite Dam. At the end of the season, inspection of STS after removal from gatewells indicated that 9 of 18 screens had not functioned properly. Some screen panels were torn and others were in such poor condition they could not have operated as designed. The higher descaling rates at Little Goose Dam were presumably from the poor condition of screening material on the STS.

Phase 3: Development and Evaluation of Screening Systems and Orifice Bypass Installations in Turbine Intakes at Lower Columbia River Dams, 1975–79

Although STS guidance systems had been chosen for Lower Granite and Little Goose dams on the Snake River, problems still existed with maintenance and operation of the screens. Further, efforts to evaluate and maintain runs of Snake River salmon and steelhead stocks were almost exclusively targeted at yearling spring and summer Chinook salmon and steelhead, though some coho and sockeye salmon stocks still existed in the basin. The majority of juveniles of these stocks migrated through the lower Snake River from early April to early June. It was only initially envisioned that STS would have to operate during this period of time.

Similar to the Snake River, yearling Chinook, coho, and sockeye salmon and steelhead smolts that originated from the mid- and upper Columbia River areas migrated through the lower Columbia River in the spring;

but additionally, a large number of subyearling summer and fall Chinook salmon smolts migrated from early June through September. Thus, while initial evaluations of STS in the Snake River found operational problems and it appeared that it would be possible to develop and maintain STS systems that could operate continuously for a couple of months in the spring, it didn't appear at first glance that it would be feasible to operate STS as configured for the 5-mo smolt-migration period in the Lower Columbia River. In addition, in 1974 NMFS proposed several studies as a first step of a research program to develop a more effective and less costly fingerling protection system for the Bonneville Dam Second Powerhouse scheduled for construction in the late 1970's, with completion due in the early 1980's.

Fish passage studies to develop a design for downstream facilities at the new Bonneville Dam Second Powerhouse began in 1975 with new measurements of vertical distribution of fish passing through turbines at Bonneville Dam First Powerhouse (Long²³). These studies were conducted because it was not certain that earlier vertical distribution measurements of smolts passing turbine intakes at The Dalles and McNary dams (Long, 1968) represented what might occur at the new Bonneville Dam Second Powerhouse with turbine intakes having much less submergence. A net frame with a single row of fyke nets was placed in the operating gateslot while a cover blocked the bulkhead gateslot (Fig. 5). A greater percentage of fish of all species were found in the upper 29% of the turbine intake at Bonneville Dam compared to 1960 and 1961 vertical distribution studies at McNary and The Dalles dams. These results suggested that something other than pressure affected the vertical distribution of fish

²²Smith, J. R., G. M. Matthews, L. R. Basham, S. Achord, and G. T. McCabe. 1980. Transportation operations on the Snake and Columbia Rivers 1979. Report to U.S. Army Corps of Engineers, Walla Walla District by NOAA, Natl. Mar. Fish. Serv., Seattle, 27 p. [avail. at https://www.nwfsc.noaa.gov/assets/26/7274_07112012_095854_Smith.et.al.1980.pdf].

²³Long, C. W. 1976. Final report on vertical distribution of fingerling salmonids in turbine intakes of the Bonneville First Powerhouse. Report to U.S. Army Corps of Engineers, Portland District by NOAA, Natl. Mar. Fish. Serv., Seattle, 11 p. [avail. at https://www.nwfsc.noaa.gov/assets/26/7134_07022012_114543_Long.1976.pdf].

in the intake because the opening to the operating gateslot at Bonneville Dam was much shallower at 11.2 m (depth below forebay surface) compared to the other two dams at approximately 19.7 m (Fig. 3).

In 1976, studies continued to begin to address two major goals needed for the Bonneville Second Powerhouse: 1) develop designs and operating criteria for submerged orifices that would efficiently pass fingerlings from gatewells into a safe bypass, and 2) develop less costly and more efficient methods to guide fish away from turbines compared to the STS systems currently undergoing testing at Lower Granite Dam (Long and Krcma²⁴). With respect to orifices, earlier studies at Snake River dams had shown that the effectiveness of orifices was related to orifice size and location, VBS configuration, and the amount of flow into the gatewell. The size and angle of turbine intake screens affected gatewell flow.

Conditions tested in the Snake River often led to poor OPE with high levels of descaling on fish remaining in gatewells, sometimes even with fish that passed through the orifices successfully. To address this, new criteria for orifices were developed to assess if orifices worked adequately. It was decided that orifices should pass 90% of fish of all salmonid species that enter gatewells within 24 h. The OPE was determined by comparing the number of fish collected in a trap on the downstream side of the orifice compared to the number of fish dipnetted from the gatewell at the end of a test, plus the total collected in the trap (Fig. 10).

The Bonneville First Powerhouse gatewells were darkened and lights placed at the downstream side of test orifices. With regard to actual orifice placement, another important criteria was that the hydraulic head required

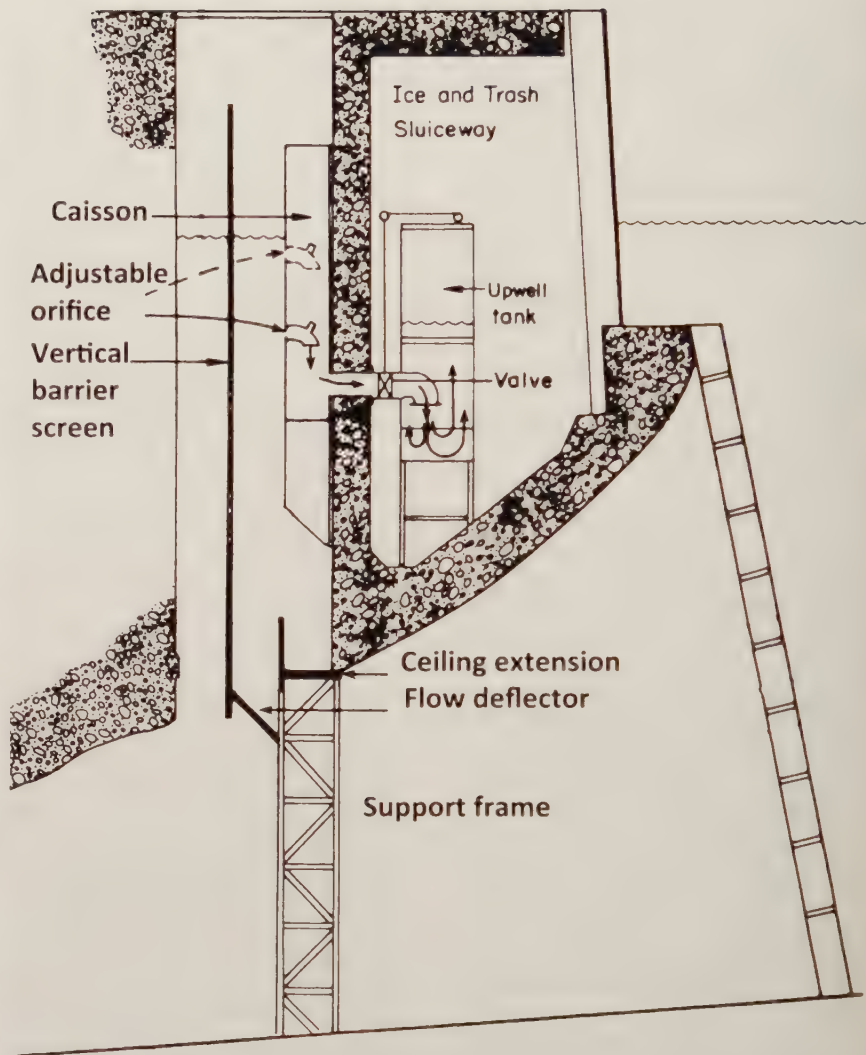


Figure 10.—Schematic configuration of orifice trap at Bonneville Dam First Powerhouse. A caisson was placed in one bulkhead gateslot to provide a configuration equivalent to what would occur within the bulkhead gateslot at the new Bonneville Dam Second Powerhouse. It also provided the ability to alter orifice head and placement. A flow deflector was installed to assure sufficient fish entered the gatewell for orifice testing. Ceiling extension added to also provide a configuration similar to the design of the bulkhead gateslot for the new Bonneville Dam Second Powerhouse.

to achieve adequate OPE should not exceed the submergence of the orifice because when the head must exceed submergence, construction of prototypes becomes much more difficult and costly. The test orifices were placed in a caisson at a distance from the VBS that would match the configuration in the new Bonneville Dam Second Powerhouse. Additionally, the VBS was blocked so that the open area

was similar to what would exist at the Bonneville Dam Second Powerhouse. Orifices with diameters of 20.3, 25.4, 30.5, and 45.7 cm diameter were tested with submergence from near the water surface to 2.4 m.

Preliminary tests indicated that 20.3 cm diameter orifices could not meet the criteria, and the 45.7 cm diameter orifices far exceeded it. Efforts focused on testing variants of the 25.4

²⁴Long, C. W., and R. F. Krcma. 1977. Development of a system for protecting juvenile salmonids at the Second Powerhouse at Bonneville Dam - Progress 1976. Report to U.S. Army Corps of Engineers, Portland District by NOAA, Natl. Mar. Fish. Serv., Seattle, 15 p. [avail. at http://www.nwfsc.noaa.gov/assets/26/7136_07022012_115128_Long.and.Krcma.1977.pdf].

and 30.5 cm diameter orifices. The 25.4 cm diameter orifices did not work well at submergences less than ~1.2 m, while the 30.5 cm diameter orifices worked well with a submergence of as little as ~0.75 m. Testing was recommended for another year to determine if one or two 30.5 cm orifices were needed to meet the 90% passage criteria.

Also in 1976, studies began to evaluate the survival of fish that passed through the gateway orifices into the ice and trash sluiceway, which emptied in the tailrace of McNary Dam (Sims and Johnsen²⁵). This was needed because no detailed studies had determined the survival of fish entering the tailrace that had passed into the ice and trash sluiceway since the orifices were added in 1969. Test fish released at night into the north outfall at McNary Dam showed about a 50% increase in mortality over fish released into the north outfall during the day and over both day and night releases into the south outfall. The increased mortality may have related to increased predator activity generated by the availability of large numbers of fingerlings normally that exited the north outfall at night. Lighting on the deck may have also enhanced predator effectiveness in the area.

Finally, in 1976, the first studies were initiated at the NMFS Pasco Field Station to test alternatives to STS (Ruehle et al.²⁶). An experimental oval flume was constructed with three pumps that provided the ability to create flows up to 2.4 m/sec. The flume was approximately 1 m wide, with a 48 m circumference and a water depth

of about 2 m. Tests were conducted on one of the 16 m long sides of the oval.

Two types of bar screens—a square bar and a triangular bar (Johnson wedge wire), with porosities of 33%, 50%, or 60%—were tested under variable velocity conditions, at different angles to the flow, with variable configurations to a downstream vertical wall (simulating the opening to a bulkhead slot), and with differing amounts of debris. Fish without descaling were released upstream of the test configuration and observed through a clear Plexiglas window on the inside wall of the flume as they approached the screen, and they were subsequently collected to measure levels of descaling.

The researchers found no serious problems with a fixed screen causing descaling on fish. The optimum configuration that minimized fish descaling and accumulation of debris appeared to consist of a flat bar screen of 50% or greater porosity with a curved deflector at the terminal end. The screen angle to direction of flow should not exceed 20° and the screen placement should position the terminal end above the downstream edge of the concrete wall that holds the VBS. The research results were sufficiently positive to justify field studies of a prototype bar screen in a turbine intake gateway.

The first field study of bar screens in gateways was conducted at Bonneville Dam First Powerhouse in 1977 (Krcma et al.²⁷). The study utilized small bar screens (1.1 m long) (Fig. 11) with 0%, 35%, or 65% porosity and fyke nets attached to a frame beneath the bar screen to collect unguided fish. The initial tests obtained FGE levels that ranged from 42% to 75% for all species. A bar screen with 0% open area guided significantly fewer fish than bar screens with 35% and 65% open area. Based on vertical dis-

tribution data from previous years, the 1977 FGE results suggested that nearly all the juvenile salmon that could be intercepted were in fact diverted into the gateways. While the FGE levels were lower than found with STS at up-river dams, they were encouraging given the small size of the guiding device. Further, descaling levels and injury to guided fish were relatively low so that plans were made to continue studies at Bonneville Dam in 1978 as well as to construct a bar screen device that could be compared to the STS for testing at McNary Dam in 1978.

Orifice research at Bonneville Dam First Powerhouse in 1977 was directed at determining maximum efficiency and configuration of 30.5 cm diameter orifices. After many tests with one or two orifices, submergences between 0.9 and 3 m, and with or without lights, it was found that between 75% and 89% OPE for all species was obtainable for orifices of 0.9 and 1.8 m submergence, respectively, in 24 h with one 30.5 cm diameter, backlit orifice with a darkened gateway. Descaling rates of collected fish remained low even when large volumes of debris were experimentally placed in the gateways with the fish. Based on these studies, it was decided that even though 90% OPE was not obtained, since the quality of fish passing through the orifice and those that did not was high, 75% OPE in 24 h was a reasonable target.

Studies also continued in 1977 to determine potential outfall mortality at McNary and John Day Dams before the installation of screening systems (Sims and Johnsen²⁸). Results suggested that the north outfall at McNary Dam did not lead to serious losses of fish, but that the outfall at John Day Dam was problematic because only a small number of fish exited to the tailrace (because no STS in turbine

²⁵Sims, C. W., and R. C. Johnsen. 1977. Evaluation of the fingerling bypass system at John Day Dam and the fingerling bypass outfall at McNary Dam. Report to U.S. Army Corps of Engineers, Portland District by NOAA, Natl. Mar. Fish. Serv., Seattle, 16 p. [avail. at www.nwfsc.noaa.gov/assets/26/7258_07112012_084342_Sims.and.Johnsen.1977.pdf].

²⁶Ruehle, T. R., C. W. Long, and M. H. Gessel. 1978. Laboratory studies of a nontraveling bar screen for guiding juvenile salmonids out of turbine intakes. Report to U.S. Army Corps of Engineers, Walla Walla District by NOAA, Natl. Mar. Fish. Serv., Seattle, 14 p. [avail. at http://www.nwfsc.noaa.gov/assets/26/6435_08122014_110849_Ruehle.et.al.1978.pdf].

²⁷Krcma, R. F., C. W. Long, and C. S. Thompson. 1978. Research on the development of a fingerling protection system of low head dams—1977. Report to U.S. Army Corps of Engineers, Portland District by NOAA, Natl. Mar. Fish. Serv., Seattle, 32 p. [avail. at http://www.nwfsc.noaa.gov/assets/26/7109_06282012_123716_Krcma.et.al.1977.pdf].

²⁸Sims, C. W., and R. C. Johnsen. 1978. Evaluation of the fingerling bypass system outfalls at McNary and John Day Dams. Report to U.S. Army Corps of Engineers, Portland District by NOAA, Natl. Mar. Fish. Serv., Seattle, 13 p. [avail. at http://www.nwfsc.noaa.gov/assets/26/7259_07112012_084556_Sims.and.Johnsen.1978.pdf].

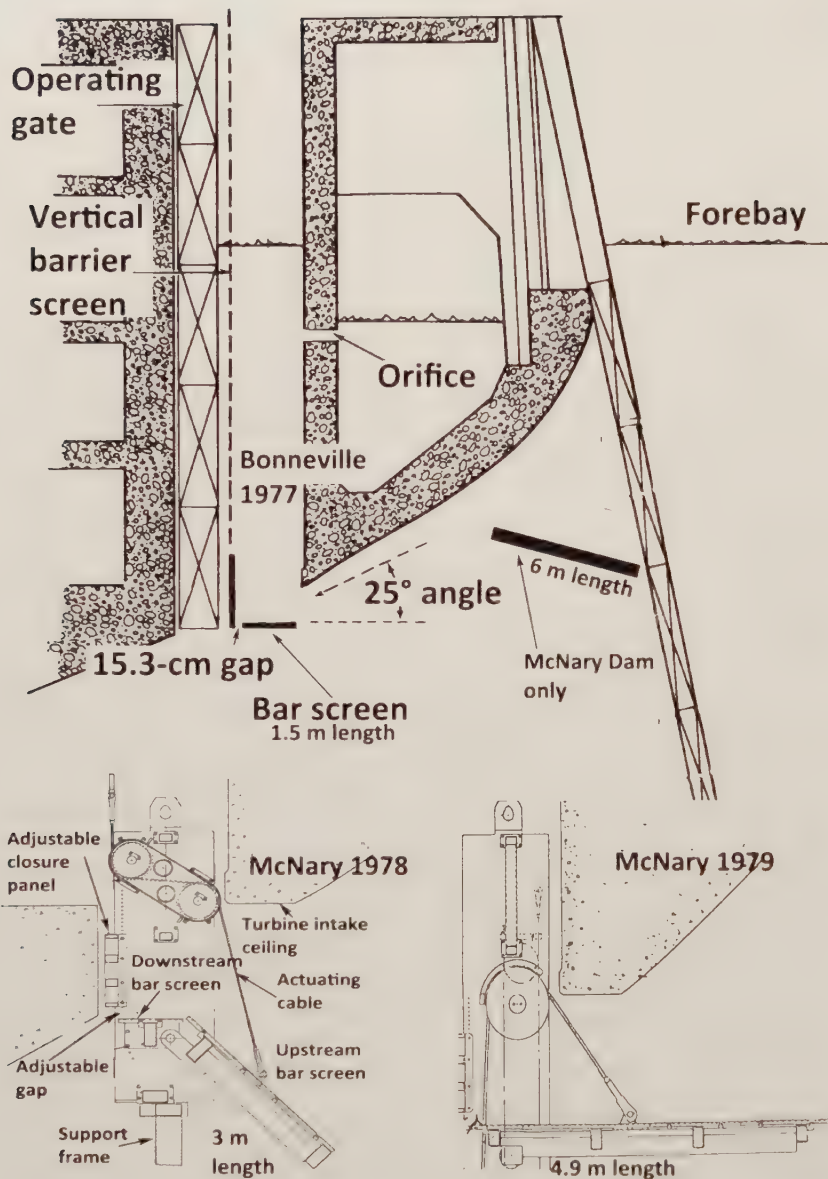


Figure 11.—Cross section of a turbine intake at Bonneville Dam First Powerhouse showing a schematic representation of the configurations used to test bar screen deflectors at Bonneville Dam in 1977 and McNary Dam in 1978/79. The deflector on the trashrack was only utilized at McNary Dam. Note the difference in the configuration of the entrance to the bulkhead gateslot from the ceiling of the turbine intake between Bonneville Dam and McNary Dam.

intakes and no VBS in gatewells), and they had high levels of mortality.

In 1978, three different bar screen configurations were tested at Bonneville Dam First Powerhouse, but none of the results were as good as those found in 1977, and all FGE results were considered inadequate (Krcma

et al.²⁹). Further, no apparent causes were identified that could explain the

²⁹Krcma, R. F., C. W. Long, C. S. Thompson, W. E. Farr, T. W. Newcomb, and M. H. Gessel. 1979. The development of an improved fingerling protection system for low head dams, 1978. Report to U.S. Army Corps of Engineers, Portland District by NOAA, Natl. Mar. Fish. Serv., Seattle, 40 p. [avail. at http://www.nwfsc.noaa.gov/assets/26/6684_10152010_142909_Krcma.et.al.1979b-rev.pdf].

much lower FGE results. Researchers speculated that a longer bar screen that could intercept a greater percentage of the flow might provide significant increases in FGE, and they recommended that the USACE consider this for future studies.

Simultaneously to the Bonneville Dam studies, a two-part bar screen system was evaluated upriver at McNary Dam (Krcma et al.³⁰). A bar screen similar to the one used at Bonneville Dam was inserted into the bulkhead gateslot and a deflecting screen was attached to the trash rack of the turbine intake (Fig. 11). The two-part guiding system was designed to intercept approximately the same amount of flow as STS. During FGE tests, the hydraulic gate in the operating gateslot was raised to increase the flow above the horizontal bar screen and into the bulkhead gateslot.

The support frame for the bar screen deflector also had fyke nets attached, which allowed the ability to measure FGE for each test condition. Additionally, a gap net was positioned at the downstream end of the bar screen to capture fish and/or debris that was intercepted but not diverted into the gatewell. Results of the bar screen tests found that FGE was higher during the day than during the night, but because tests were mostly conducted over a period that included day and night conditions, most data were a combination of overall guidance. A comparison was made between the 2-part bar screen FGE results and what was considered theoretically obtainable based on the vertical distribution data gathered in 1961. The 2-part system tended to guide considerably fewer sockeye and Chinook salmon than expected, but steelhead were guided at about the theoretical maximum. It was not easy

³⁰Krcma, R. F., W. E. Farr, and C. W. Long. 1980. Research to develop passive bar screens for guiding juvenile salmonids out of turbine intakes at low head dams on the Columbia and Snake Rivers, 1977-1979. Report to U.S. Army Corps of Engineers, Portland District by NOAA, Natl. Mar. Fish. Serv., Seattle, 28 p. [avail. at https://www.nwfsc.noaa.gov/assets/26/8975_11302016_111431_Krcma.et.al.1980-SBS.pdf].

to get a perfect comparison to guidance with an STS. A very incomplete bypass system existed and only four turbines had VBS. However, some very cursory tests in turbine intake slot 4B with an STS indicated that across all species, overall FGE was approximately 68% compared to only 25% on similar days for the bar screen, and 7% in turbine intake 7B with no screens at all. The bar screen deflector increased descaling minimally, 1–1.5%, when compared to fish removed from gatewells with no guidance device.

Based on the OPE results at Bonneville Dam in 1976–77, the two 15.2 cm diameter orifices in each turbine intake gatewell at McNary Dam were bored to a 30.5 cm diameter size. In 1978, tests of one or two 20.3 cm diameter orifices (inserts placed into the 30.5 cm diameter orifices) were compared against one 30.5 cm diameter orifice. After testing, researchers recommended using one 30.5 cm diameter orifice in each gatewell because less debris could clog an orifice and overall guidance between the two smaller orifices and the larger orifice were similar.

For the 1979 testing season at McNary Dam, the USACE redesigned the gatewell deflector to increase the length to 4.9 m from the previous year's 2.5 m, while the trash rack deflector remained the length used in 1978 (Fig. 11.) For tests, one bar screen and one trash rack deflector was installed in all three intakes of the test turbine. Tests evaluated three different screen porosities created by using different panels of wedge wire with different inter-spaces (Krcma et al.³⁰).

Efficacy of different bar screen combinations was evaluated by comparing FGE of the bar screen results to FGE results with STS, levels of descaling, and swimming performance of a sample of fish removed from the gatewell. Descaling and swimming performance of fish volitionally entering adjacent gatewells without a guidance device were used as controls. The 2-part bar screen guidance system performed nearly the same as STS for most salmonid smolts, with the exception of

sockeye and juvenile Chinook salmon < 70 mm in length. The guidance for bar screens of 52% and 62% porosity was consistently higher than the 35% porosity. However, bar screens with an interspace of 3.2 mm impinged excessive numbers of juvenile lamprey, *Lampetra* spp., and subyearling Chinook salmon of < 70 mm fork length if the angle-to-flow exceeded 45°. The percentage of descaled fish (all species) was low for both the bar screen and STS, and fish guided into gatewells by screens had similar descaling to fish recovered from gatewells without screening devices. Likewise, swimming stamina tests for all groups had similar results.

The conclusion drawn from the 3 yr of bar screen studies were that passive bar screens provided a potentially viable method for guiding juvenile salmonids from turbine intakes, although their use was more limited than STS. Caveats for the bar screen were that they would potentially not work well if the vertical distribution of fish in the turbine intakes was too low, fish were too small, or ambient water velocities in turbine intakes were too high. Further, development of some method to remove accumulated debris from the screens was required, other than the costly method used in the test studies to back-flush the screens.

Assessment of Bypass Development to Date, 1980

In the Snake River, with the exception of the indirect estimate of low FGE at Lower Granite Dam in 1979—a value attributed to debris on trash racks—it appeared the STS could guide more than 70% of migrants entering turbine intakes into gatewells. Descaling of fish in gatewells was attributed to problems with damaged mesh on STS and undersized orifices. Orifice sizes were increased at Lower Granite and Little Goose dams.

Somewhat discouragingly, however, as part of a 1980 study to estimate survival of juveniles passing dams on the lower Snake and Columbia Rivers, it was determined through deductive models that the estimated percent-

age of the smolt run arriving at Lower Granite Dam that was collected by the STS/orifice systems was approximately 36% and 51% for Chinook salmon and steelhead smolts, respectively (Sims et al.³¹); levels that were considerably lower than the target of 70%. Furthermore, these estimates were similar to those of 1979, even though most of the debris that existed in 1979 had been removed. Thus, it didn't appear that debris on the trash rack in 1979 was the cause for the estimated low guidance. However, the results of the 1980 studies were not finalized until the winter of 1980–81, which was too late to plan for additional studies at Snake River dams in spring 1981.

Some of the lower guidance by screens was attributed to an incorrect construction of the upper framework on the new variable-angle STS such that the throat opening to the bulkhead gateslot was restricted (Fig. 12). While not affecting steelhead FGE to the same extent, it may have caused hydraulic conditions that impeded the collection of Chinook salmon. On a positive note, descaling rates of Chinook salmon smolts in gatewells at Lower Granite Dam were consistently low throughout the year. Steelhead descaling rates were somewhat higher, but it appeared much of it occurred upstream of the dam.

Nonetheless, the debris at lower Granite Dam did continuously cause issues with partial plugging of orifices. To alleviate this required close monitoring of orifices and frequently closing each orifice, back flushing to remove debris, and then reopening to obtain unobstructed flow. At Little Goose Dam, however, the newly installed 30.5 cm diameter orifices worked so well that in 1980 it was difficult to dipnet enough fish from

³¹Sims, C. W., J. G. Williams, D. A. Faurot, R. C. Johnsen, and D. A. Brege. 1981. Migrational characteristics of juvenile salmon and steelhead in the Columbia River Basin and related passage research at John Day Dam, Volumes I & II. Report to U.S. Army Corps of Engineers, Portland District by NOAA, Natl. Mar. Fish. Serv., Seattle, 360 p. [avail. at https://www.nwfsc.noaa.gov/assets/26/7268_07112012_091428_Sims.et.al.1981.pdf].

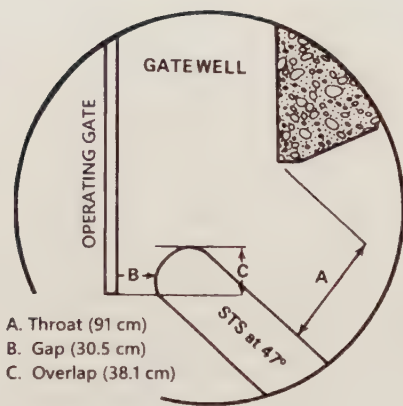


Figure 12.—Schematic showing the three critical dimensions of the upper part of a turbine intake screen lowered into the ‘standard’ position within the bulkhead slot at Bonneville Dam First Powerhouse. The three critical dimensions varied among dams as different dams had different ceiling intake and bulkhead slot configurations. When measured, guidance was lower than expected, often during the field research the screens were lowered to increase the throat area. This often then required putting in false ceilings to limit the gap opening or assure sufficient overlap existed to prevent fish passing over the screen, out through the gap, and into the turbine.

gatewells to get good measurements of descaling caused by STS (Smith et al.³²).

Decisions were necessary on how to proceed with bypass system installation at dams. After 3 yr of testing bar screen devices at Bonneville and McNary Dams, it was determined that more design and testing of bar screens would need to occur before it was possible to consider implementing them (Krcma et al.²⁹). This was not considered a near-term viable option. Thus, efforts were focused on the use of STS. Understanding the estimated poor FGE at Lower Granite Dam in 1980 was critical. A closer review of previous FGE

results with a comparison to 1980 estimates suggested that most evaluations of potential STS effectiveness were potentially biased high.

The bias may have resulted from hose releases that did not adequately represent the natural migrant population, or differences in absolute recaptures of migrants (either marked or unmarked) migrating downstream and subsequently removed from gatewells with and without STS didn’t represent the entire population entering a turbine intake. These concerns had always existed, but concerns about fish losses from using fyke nets took precedence. The review confirmed that more rigorous testing at Snake River dams was needed. On the other hand, the limited FGE research at McNary Dam with STS and fyke-net frames under the STS suggested that 70% or greater FGE for yearling salmonid migrants, with the exception of sockeye salmon, was obtainable with a STS. Because the Columbia River Fisheries Council had determined that developing a workable juvenile bypass system at John Day was a high priority, the USACE decided to move forward with development and installation of STS at dams in not only the Snake River, but also in the lower Columbia River, in addition to finishing installation of STS in all turbine intake gatewells at McNary Dam.

From a research standpoint, the review of data made it clear that despite increased mortality of migrants that would occur, to attain the information needed to make decisions on the effectiveness of STS would require more complete evaluations that compared numbers of fish that entered gatewells in turbine intakes with a guidance device to estimated numbers of fish that passed under the guidance device and were lethally captured in fyke nets attached below the device. This recommendation was presented to USACE and federal, state, and tribal fishery agencies. It was reluctantly accepted as necessary but with concern about fish losses due to sampling. Agreements were made to minimize fyke netting under STS to the extent pos-

sible while still providing the information on FGE needed for management decisions.

Clearly, developing effective systems to divert fish from passing through turbines also required that the systems would minimize adverse effects on fish. Descaling of fish was a particular problem identified in some cases. It could occur from fish interactions directly with a screening device or after fish were diverted into gatewells and as a result of interactions with the VBS caused by turbulence. Turbulence varied with the screening types and the amount of flow going into the bulkhead slot. Finally, while the initial installation of 15.2 cm diameter orifices were based on some early work at Ice Harbor Dam suggesting that they would work sufficiently well, it soon became clear on evaluation of orifices at other dams that they did not. Smaller orifices did not pass fish out of gatewells nearly as effectively as larger diameter orifices. Further, the longer fish stayed in gatewells, the more interaction they had with debris and VBS; thus, leading to higher descaling rates. This led to concern about the overall time fish spent in gatewells. As a consequence, the basis for an effective orifice system was changed from not only having low descaling rates for fish within gatewells, but also that 75% or greater of fish entering a gatewell must pass through the installed orifices within 24 h (Ruehle et al.²⁶).

Phase 4: STS Evaluations and Orifice Research at Lower Columbia River Dams, 1981–85

McNary Dam

In 1981, studies to develop a bypass system for John Day Dam commenced at McNary Dam and were conducted there for economic and practical reasons (Swan et al.³³). Much of the

³²Smith, J. R., G. M. Matthews, L. R. Basham, B. H. Monk, and S. Achord. 1981. Transportation operations on the Snake and Columbia River, 1980. Report to U.S. Army Corps of Engineers, Walla Walla District by NOAA, Natl. Mar. Fish. Serv., Seattle, 31 p. [avail. at https://www.nwfsc.noaa.gov/assets/26/7273_07112012_094308-Smith.et.al.1981.pdf].

³³Swan, G. A., R. F. Krcma, and C. W. Long. 1982. Research to develop an improved fingerling protection system for John Day Dam, 1981. Report to U.S. Army Corps of Engineers, Portland District by NOAA, Natl. Mar. Fish. Serv., Seattle, 22 p. [avail. at <http://www.nwfsc.noaa.gov>].

needed equipment was already on site at McNary Dam, and it was possible to raise the operating gates at McNary Dam to simulate flow conditions into the gatewell that would occur at John Day Dam. While not exactly the same, the configuration of the two dams was at the time considered similar enough that results at McNary Dam would apply to John Day Dam.

The average FGE (John Day condition with no operating gate) for yearling Chinook salmon and steelhead was 75% and 79%, respectively, based on a series of tests with fyke nets mounted below the STS. Test orifices were located at submergences of 2.4 and 5.2 m, with the deeper orifice simulating a John Day Dam configuration, the shallower one for McNary Dam. The OPE was unacceptable. In general, OPE was better for the McNary condition than for the John Day condition, but OPE only exceeded 75% for steelhead. Turbulence in the gatewell caused by increased water flow due to the lack of a stored operating gate was considered the probable reason for the low OPE.

Because of the poor OPE in 1981, in 1982 studies at McNary Dam to develop information for John Day Dam were focused on determining the information needed for orifice placement and operation (Krcma et al.³⁴). Secondly, FGE studies were conducted for a John Day condition (raised operating gate) and a McNary condition (stored operating gate) to evaluate subyearling Chinook guidance because the preliminary 1979 research at McNary Dam with the new variable-angled STS indicated potentially unacceptable FGE for subyearling Chinook salmon migrating in the summer.

As part of the conditions tested, a new VBS designed by the USACE

was installed into gatewells of the two turbines used for FGE tests. The new design created an overall VBS porosity of 15%, attained by the addition of a perforated plate on the screen to balance the velocity of water through the screen to a uniform 15 cm/s. The polyester mesh screen had a spacing of 2.4 vertical and 2.4 horizontal, 1 mm strands per cm². The screen was designated a balanced-flow vertical barrier screen (BFVBS). Compared to a standard VBS, it improved flow into and decreased the turbulence within the gatewell. It was hoped that the new BFVBS would improve conditions within the gatewell that would lead to higher OPE. The OPE tests included a range of submergences from 1.8 to 6.1 m and head over the orifice between 1.2 and 2.1 m.

The OPE levels for gatewells equipped with BFVBS were generally acceptable throughout the range of orifice submergences and heads tested, provided the test duration was greater than 24 h and the orifices were back-lighted. The OPE tests of 48 h duration did not cause a significant increase in descaling. Because flow conditions varied between gatewells and turbines, additional studies were recommended before determining where to place orifices (south or north side of gatewells). Sufficient data were collected to recommend installation of a single 30.5 cm diameter orifice at a depth of 4.8 m below full pool (summer conditions) which would provide a submergence of 2.1 m at the minimum pool level which often occurs during the spring migration. Gatewells should also have BFVBS.

The mean FGE for subyearling Chinook salmon was approximately 50%, a value significantly lower than that measured on yearling Chinook salmon and steelhead (75% and 85%, respectively). Because there was high variability in results and debris buildup on barrier screens during subyearling Chinook salmon migrations, additional testing was recommended to attain more precise FGE estimates for subyearling Chinook salmon and its relationship to levels of debris on BFVBS,

fish size, and fish condition. In addition, it was recommended that a provision for routine cleaning of BFVBS was needed to assure that debris obstruction did not negate the flow through the screens.

Finally, in 1982, intermittent operation of STS was tested to determine if it were possible to decrease wear on STS without impacting guided smolts (McCabe and Krcma³⁵). Intermittent operation of STS did not increase impingement rates for yearling Chinook salmon and steelhead or descaling rates when compared to full-time operation. Approximately 1.3% of subyearling Chinook salmon was impinged on the STS during the non-operating phase. Even with this low mortality percentage, because millions of fall Chinook salmon enter the turbine intakes, it was deemed an unacceptable number of mortalities. It was concluded that during the early spring when juvenile steelhead trout and yearling Chinook salmon migrate, STS could be operated intermittently as tested because the large fish were not impinged.

The poor FGE results in 1982 for subyearling Chinook salmon led to more directed investigations between 18 July and 9 August during the 1984 summer outmigration (Krcma et al.³⁶). Research results indicated that theoretical FGE varied considerably, but progressively decreased from a high of 77% in mid-July to a low of 56% in early August. Concurrently FGE for subyearling Chinook salmon was variable and unacceptably low for all tests. In the first three sets of tests, FGE was measured with a BFVBS, and in the last set with a VBS.

[gov/assets/26/7300_07162012_091349_Swan.et.al.1982.pdf](http://www.nwfsc.noaa.gov/assets/26/7300_07162012_091349_Swan.et.al.1982.pdf)].

³⁴Krcma, R. F., M. H. Gessel, and F. J. Ossiander. 1983. Research at McNary Dam to develop and implement a fingerling protection system for John Day Dam. Report to U.S. Army Corps of Engineers, Portland District by NOAA, Natl. Mar. Fish. Serv., Seattle, 24 p. [avail. at http://www.nwfsc.noaa.gov/assets/26/7111_07022012_092423_Krcma.et.al.1983.pdf].

³⁵McCabe, G. T., and R. F. Krcma. 1983. Effects of intermittent operation of submersible traveling screens on juvenile salmonids, 1982. Report to U.S. Army Corps of Engineers, Walla Walla District by NOAA, Natl. Mar. Fish. Serv., Seattle, 29 p. [avail. at http://www.nwfsc.noaa.gov/assets/26/7173_07042012_101215_McCabe.and.Krcma.1983.pdf].

³⁶Krcma, R. F., G. A. Swan, and F. J. Ossiander. 1985. Fish guiding and orifice passage efficiency tests with subyearling Chinook salmon, McNary Dam, 1984. Report to U.S. Army Corps of Engineers, Walla Walla District by NOAA, Natl. Mar. Fish. Serv., Seattle, 29 p. [avail. at http://www.nwfsc.noaa.gov/assets/26/6685_10152010_150739_Krcma.et.al.1984b-rev.pdf].

In the first two sets of tests in mid-July, FGE averaged 34% and 39%; they were conducted post-dusk. In the third set of tests in late July conducted pre-dusk, FGE averaged 46%. The last set of tests from 7 to 9 August was also conducted pre-dusk, but FGE only averaged 33%. It appeared that the BFVBS increased the potential FGE, but no clear indications existed to explain the overall low FGE for subyearling migrants other than they passed into the turbine intakes at a lower level than yearling migrants in the spring. The BFVBS had been slightly modified by removing part of the solid panel at the top to provide more flow toward the orifice. This resulted in successful OPE tests. With the modified BFVBS, OPE averaged more than 75% within 24 h for all sets of tests.

John Day Dam

Based on research results from McNary Dam, the John Day Dam juvenile salmonid collection and passage system was rehabilitated and evaluations of it began in 1985 (Krcma et al.³⁷). The 54° angled STS produced FGE of 72%, 41%, and 86% for yearling Chinook salmon, sockeye salmon, and steelhead, respectively, while not causing excessive descaling. The FGE for subyearling Chinook salmon was a disturbingly low 21%. When the FGE of subyearling Chinook salmon was compared to the percentage of fish captured in the vertical distribution fyke nets, only about 40% of the fish considered guidable were, in fact, guided. The comparison of FGE to the percentage of fish considered guidable was termed theoretical FGE (TFGE). The TFGE value and absolute FGE values were lower than expected based on results of testing the John Day conditions tested at McNary Dam in 1982.

Direct estimates of OPE were only obtained for yearling Chinook salmon and steelhead and they were 71.7% ± 25% and 53.2% ± 14.9%, respectively. Indirect OPE estimates for yearling Chinook salmon (76.8%) and sockeye salmon (78.4%) exceeded the goal of 75%, but subyearling Chinook salmon (71.3%) and steelhead (66.5%) were slightly below the goal. The tests in 1985 were conducted on a partially completed bypass system that led to a head on the orifices during OPE tests that was nearly double (2.2 m) the head that would exist on a completed bypass system.

Thus, OPE tests were repeated in 1986, however, results were similar to those obtained in 1985 (Brege et al.³⁸). Additionally, since the FGE tests for subyearling Chinook salmon were only conducted over a 3-day period in 1985, in 1986 repeat evaluations of FGE over a longer period during the summer were also conducted with an overall average FGE of 35%. The results were higher than in 1985 but still far below target values.

Bonneville Dam First Powerhouse

Although the decision had been made to move forward with STS at all dams, in 1981 at the Bonneville First Powerhouse one last effort to evaluate the feasibility of a possible alternative to STS was considered: To open gates on the ice and trash sluiceway to create a surface flow into the sluiceway that would attract fish into it as they approached the powerhouse rather than milling around in surface waters during daylight conditions before passing downward into the turbine intakes in the evening hours.

At Bonneville Dam First Powerhouse, adjustable-angle STS initially tested at McNary Dam in 1979 were evaluated in Turbine Unit 4 against

fish passing into the ice and trash sluiceway (Krcma et al.³⁹). The STS could be positioned at three elevations within the turbine intake in 15.2 cm increments, and the screen surface set to four different angles (47°, 53°, 60°, and 65° measured up from vertical). These two adjustments allowed considerable flexibility to change the throat opening, gap opening, overlap, and the percent of the total turbine intake flow intercepted by the STS in the operating position (Fig. 12).

As noted above, it was tested with a full array of fyke nets on a frame below the screen in order to provide good estimates of fish not guided into gatewells compared to those captured from the gatewell. Finally, TFGE was estimated based on recovery of fish from vertical distribution fyke nets. Research was also conducted to determine if it was possible to cycle orifices off and on (2 h and 1 h or 4 h and 2 h) and obtain acceptable OPE compared to orifices operated continuously, with the intent to determine if the amount of debris and orifice clogging would decrease with less orifice operation.

Initially, all three STS's were set at the lowest elevation (13.3 m mean sea level) and at the smallest angle (47°). The standard test configuration had the three STS's in turbine Unit 4, with the bar screen device in an adjacent gatewell (either 3C or 5A). During the period 30 April–6 June, a total of 36 guidance tests were conducted. The results of these tests found FGE in excess of 70% for nearly all species when the STS was set at a 47° angle and operated at the 13.3 m elevation.

The FGE was lowest for subyearling Chinook salmon (71.5%) due primarily to loss through the gap (8.7%) at the top of the screen. The quality of STS guided fish was acceptable, with only

³⁷Krcma, R. F., D. A. Brege, and R. D. Ledgerwood. 1986. Evaluation of the rehabilitated juvenile salmonid collection and passage system at John Day Dam - 1985. Report to U.S. Army Corps of Engineers, Portland District by NOAA, Natl. Mar. Fish. Serv., Seattle, 25 p. [avail. at https://www.nwfsc.noaa.gov/assets/26/6686_10152010_151929_Krcma.et.al.1986-rev.pdf].

³⁸Brege, D. A., D. R. Miller, and R. D. Ledgerwood. 1987. Evaluation of the rehabilitated juvenile salmonid collection and passage system at John Day Dam - 1986. Report to U.S. Army Corps of Engineers, Portland District by NOAA, Natl. Mar. Fish. Serv., Seattle, 37 p. [avail. at https://www.nwfsc.noaa.gov/assets/26/8852_09142016_180754_Brege.et.al.1997.pdf].

³⁹Krcma, R. F., D. DeHart, M. H. Gessel, C. W. Long, and C. W. Sims. 1982. Evaluation of submersible traveling screens, passage of juvenile salmonids through the ice-trash sluiceway, and cycling of gatewell-orifice operations at Bonneville First Powerhouse, 1981. Report to U.S. Army Corps of Engineers, Portland District by NOAA, Natl. Mar. Fish. Serv., Seattle, 25 p. [avail. at http://www.nwfsc.noaa.gov/assets/26/7110_07022012_092050_Krcma.et.al.1982.pdf].

minor differences noted in descaling rates between test and control fish. Vertical distribution measurements of fish indicated TFGE ranged from 75% to 90%.

Subyearling Chinook and sockeye salmon were generally more deeply distributed than steelhead. The FGE was generally 2-times greater compared to fish passing through sluiceways into the ice and trash sluiceway. Because it appeared that the adjustable-angle STS was a workable option, no additional research was scheduled for the next year, and the process of developing designs for installation of STS in all the turbines at Bonneville Dam First Powerhouse was started.

Unfortunately, OPE was less than 30% after 24 h of operation for all test and control conditions. After 72 h of operation, orifices that were operated continuously attained OPE levels of 85%; however, OPE of cycled orifices changed little from values seen after 24 h of operation. None of the orifice results met the OPE target of 75% of fish leaving a gatewell within 24 h of entering, nonetheless, as part of the STS installation, 30.5 cm diameter orifices were drilled into all gatewells.

In 1984, OPE studies were again conducted. Because of debris loads in gatewells and concerns about potential plugging of orifices, comparisons were made between 30.5 cm diameter and 35.6 cm diameter orifices (Gessel et al.⁴⁰). Target species were yearling and subyearling Chinook salmon. Tests were conducted in May, when yearling fish dominated the catch, and in June and July, when mostly subyearling chinook salmon were present. For yearling Chinook salmon, average OPE estimates were 70% for the 35.6 cm diameter orifice and 73% for the 30.5 cm diameter orifice, but there was no significant difference between the two.

In the summer, the average OPE for subyearling Chinook salmon was 85%.

In 1985, studies were repeated to determine if OPE differences existed between gatewells with VBS or BFVBS, and, to decrease variability of the results, only the 35.6 cm diameter orifices tested in 1984 were used (Gessel et al.⁴¹). The OPE did not vary based on VBS type and was higher than observed in 1984. For yearling Chinook salmon, OPE ranged from 82% to 93% and it exceeded 90% for all other yearling migrants. For subyearling Chinook salmon, OPE varied throughout the summer, ranging from 85% in early summer to 39% in late summer, with a weighted average of 64%.

The most important finding was that orifices did not successfully pass fish from gatewells if the head over them was less than 75 cm—a height that produced a velocity of water through the orifices of approximately 3.75 m/s. This was determined when an early morning inspection of the gatewells found that all of them contained 2,000–5,000 smolts. For power production purposes, water used from the reservoir had dropped the forebay level by approximately 60 cm. This was within the normal operating range of the forebay, but it was outside what could occur with the new fish bypass system installed at Bonneville Dam. As a consequence, the operating rules for the forebay were changed to require the reservoir to stay within 30 cm of full pool during periods when downstream fish passage occurred. Orifice sizes at Bonneville Dam First Powerhouse were increased to 35.6 cm diameter.

Bonneville Dam Second Powerhouse

In 1982, the smolt collection system at Bonneville Dam Second Powerhouse was completed, and an evaluation of the system began in 1983

(Krcma et al.⁴²). Guiding efficiency of the STS was disturbingly low for all species and all conditions tested. Research to assess changes to the STS, dam, and dam operations occurred over the next 6 yr in an attempt to improve FGE (Gessel et al.^{40, 41, 43, 44, 45, 46}). A summary of these efforts was previously published by Gessel et al. (1991).

Additionally, in 1983 initial research was conducted to determine OPE for the new system (Krcma et al.³⁹). A series of four tests was conducted between 26 April and 3 May. The OPE was 66% for steelhead, 66% for yearling Chinook salmon, 64% for coho salmon, 59% for sockeye salmon, and 85% for subyearling Chinook salmon. Additional OPE testing was delayed until a more acceptable FGE was achieved.

⁴²Krcma, R. F., M. H. Gessel, W. D. Muir, C. S. McCutcheon, L. G. Gilbreath, and B. H. Monk. 1984. Evaluation of the juvenile collection and bypass system at Bonneville Dam -- 1983. Report to U.S. Army Corps of Engineers, Portland District by NOAA, Natl. Mar. Fish. Serv., Seattle, 68 p. [avail. at http://www.nwfsc.noaa.gov/assets/26/7112_07022012_092841_Krcma.et.al.1984a.pdf].

⁴³Gessel, M. H., L. G. Gilbreath, W. D. Muir, B. H. Monk, and R. F. Krcma. 1987. Evaluation of the juvenile collection and bypass systems at Bonneville Dam - 1986. Report to U.S. Army Corps of Engineers, Portland District by NOAA, Natl. Mar. Fish. Serv., Seattle, 54 p. [avail. at https://www.nwfsc.noaa.gov/assets/26/7000_05212012_085026_Gessel.et.al.1987b.pdf].

⁴⁴Gessel, M. H., B. H. Monk, and J. G. Williams. 1987. Continuing studies to improve and evaluate the fingerling collection and bypass systems at Bonneville Dam. Report to U.S. Army Corps of Engineers, Portland District by NOAA, Natl. Mar. Fish. Serv., Seattle, 17 p. [avail. at https://www.nwfsc.noaa.gov/assets/26/6999_05212012_083425_Gessel.et.al.1987a.pdf].

⁴⁵Gessel, M. H., B. H. Monk, D. A. Brege, and J. G. Williams. 1989. Fish guidance efficiency studies at Bonneville Dam First and Second powerhouses - 1988. Report to U.S. Army Corps of Engineers, Portland District by NOAA, Natl. Mar. Fish. Serv., Seattle, 36 p. [avail. at https://www.nwfsc.noaa.gov/assets/26/7002_05212012_085721_Gessel.et.al.1989a.pdf].

⁴⁶Gessel, M. H., D. A. Brege, B. H. Monk, and J. G. Williams. 1990. Continued studies to evaluate the juvenile bypass systems at Bonneville Dam - 1989. Report to U.S. Army Corps of Engineers, Portland District by NOAA, Natl. Mar. Fish. Serv., Seattle, 34 p. [avail. at https://www.nwfsc.noaa.gov/assets/26/7003_05212012_091315_Gessel.et.al.1990.pdf].

⁴⁰Gessel, M. H., R. F. Krcma, W. D. Muir, C. S. McCutcheon, L. G. Gilbreath, and B. H. Monk. 1985. Evaluation of the juvenile collection and bypass systems at Bonneville Dam - 1984. Report to U.S. Army Corps of Engineers, Portland District by NOAA, Natl. Mar. Fish. Serv., Seattle, 76 p. [avail. at https://www.nwfsc.noaa.gov/assets/26/6996_05212012_082052_Gessel.et.al.1985a.pdf].

⁴¹Gessel, M. H., L. G. Gilbreath, W. D. Muir, and R. F. Krcma. 1986. Evaluation of the juvenile collection and bypass systems at Bonneville Dam - 1985. Report to U.S. Army Corps of Engineers, Portland District by NOAA, Natl. Mar. Fish. Serv., Seattle, 103 p. [avail. at https://www.nwfsc.noaa.gov/assets/26/6998_05212012_083107_Gessel.et.al.1986.pdf].

Phase 4: Research and Development to Improve FGE and OPE at Lower Granite Dam, 1982–85

In 1982, following analyses and planning in 1980–81, FGE studies with fyke nets began at Lower Granite Dam, as well as additional OPE studies based on recent results of OPE studies at McNary Dam (Swan et al.⁴⁷). To complement the FGE studies, new vertical distribution studies with fyke nets were conducted in turbine intakes to estimate the percentage of fish that passed above the area of flow that the STS was estimated to intercept and to develop TFGE estimates. For evaluation of actual FGE, a full array of fyke nets was placed below STS so that an absolute measure of FGE was determined. The results from studies indicated that the TFGE was 76% for Chinook salmon and 92% for steelhead, while the average FGE (over six test conditions) was an unacceptable 50.7% for Chinook salmon, but 73.5% for steelhead. The minimum acceptable FGE level was set at 70%. The OPE of the 20.3 cm diameter orifices was unacceptable for Chinook salmon and steelhead; averaging 60.5% and 24%, respectively.

Additionally, intermittent operation of STS was conducted at Lower Granite (as it was at McNary Dam in 1982) to determine if it were possible to decrease screen operation while not impacting fish quality. Early in the spring and summer run, intermittent STS operation—15 minutes off and 1.5 minutes on—was tested (McCabe and Krcma⁴⁸). It did not increase impinge-

ment rates for yearling Chinook salmon and steelhead or descaling rates when compared to fulltime operation.

Based on the 1982 studies, during the fall the USACE contracted a hydraulic model study of a turbine intake at Lower Granite Dam. The model study found that the STS deflected a larger than expected proportion of flow downward and theoretically caused the lower than expected FGE. As potential solutions, some additional hydraulic modeling indicated that raising the operating gate and lowering the STS could possibly reduce the flow deflection. An installation of at least one larger, 27.9 cm diameter orifice was recommended. This would provide flow with the equivalent of two 20.3 cm diameter orifices.

To avoid OPE bias between a north and a south orifice, it was recommended to modify a BFVBS by removing one solid plate at the top and replacing it with a porous one, with the intent to direct flow toward one orifice. While it appeared feasible to operate the STS without increasing problems for migrating fish during the spring, the practice was not accepted as a general guideline by fisheries agencies because of an inability to monitor STS continuously to determine if screening systems would begin to plug up over short time periods.

In 1983, several different conditions were tested to potentially improve FGE (Swan et al.⁴⁹). The STS was tested in a standard and lowered 0.6 m position. The latter condition increased the throat opening from 0.9 to 1.5 m, which allowed more flow to pass through the gap area. Results of testing indicated that lowering the screen had little to no effect on FGE. When the solid plate of the STS behind the traveling mesh was replaced with a perforated plate to increase the porosity of the STS, the gap net catch decreased,

which suggested more fish migrated above the screen and potentially fewer impinged on the screen. The different STS combinations were tested with the operating gate in the standard, 1.5 m and 6.1 m raised position.

Interestingly, FGE was higher for Chinook salmon when the migration was comprised of mostly Chinook salmon; likewise, FGE was higher for steelhead when the catch was comprised mostly of steelhead. This suggested some behavioral interaction between species may have resulted in different vertical distributions of the fish within the water column. While raising the operating gate increased flow into the bulkhead gateslot, and increased FGE significantly over the control condition, only the operating gate raised 6.1 m led to FGE levels >70% for yearling Chinook salmon. All steelhead FGE levels were above 80% for all raised gate positions.

The OPE of a single 30.5 cm diameter orifice was tested with different combinations of plates on a balanced-flow vertical barrier screen. Descaling rates of fish in gatewells were low in all the different screen and operating gate configurations. The single 30.5 cm diameter orifice had about the same OPE as the combined two 20.4 cm diameter orifices for Chinook salmon and steelhead. For the former, OPE averaged approximately 70%, but for the latter only about 50%. These values were below the minimum target of 75%.

Based on the 1983 studies, it was recommended to permanently raise the operating gate 6.1 m or remove it entirely from the operating gateslot. However, it was clear that raising the gate increased flow turbulence in the bulkhead gateslot, and additional tests on the effects of the increased flow on OPE were needed.

In 1984, FGE at Lower Granite Dam was again tested, but this time with the operating gate raised 18.8 m (Swan et al.⁵⁰). This height was hy-

⁴⁷Swan, G. A., R. F. Krcma, and F. J. Ossiander. 1983. Studies to improve fish guiding efficiency of traveling screens at Lower Granite Dam. Report to U.S. Army Corps of Engineers, Walla Walla District by NOAA, Natl. Mar. Fish. Serv., Seattle, 20 p. [avail. at http://www.nwfsc.noaa.gov/assets/26/7301_07162012_091738_Swan.et.al.1983.pdf].

⁴⁸McCabe, G. T., and R. F. Krcma. 1983. Effects of intermittent operation of submersible traveling screens on juvenile salmonids, 1982. Report to U.S. Army Corps of Engineers, Walla Walla District by NOAA, Natl. Mar. Fish. Serv., Seattle, 29 p. [avail. at http://www.nwfsc.noaa.gov/assets/26/7173_07042012_101215_McCabe.and.Krcma.1983.pdf].

⁴⁹Swan, G. A., R. F. Krcma, and F. J. Ossiander. 1984. Research to develop an improved fingerling protection system at Lower Granite Dam. Report to U.S. Army Corps of Engineers, Walla Walla District by NOAA, Natl. Mar. Fish. Serv., Seattle, 27 p. [avail. at http://www.nwfsc.noaa.gov/assets/26/7302_07162012_092658_Swan.et.al.1984.pdf].

⁵⁰Swan, G. A., R. F. Krcma, and F. J. Ossiander. 1985. Development of an improved fingerling protection system for Lower Granite Dam - 1984. Final Report to U.S. Army Corps of Engineers,

draulically essentially similar to removing the operating gate. A new trash boom was installed in the forebay of the dam and especially during high spill, it appeared to adversely impact FGE for Chinook salmon but not for steelhead whose measured FGE values consistently were above 80%. In late April with spill of 40%, however, FGE for Chinook averaged only 37%. When spill decreased to 25% of flow in early May, FGE of Chinook salmon averaged 65%. The BFVBS did not significantly affect FGE, however, the gateway equipped with the BFVBS did provide significantly lower descaling rates and better OPE than a gateway equipped with VBS. Further the modified BFVBS attained OPE for Chinook salmon and steelhead of 98% and 86%, respectively, with a single 30.5 cm diameter orifice.

Because of uncertainty about the effect of the trash boom, a version of the 1984 FGE studies was repeated in 1985 in turbine intakes 4A and 4B along with simultaneous vertical distribution measurements in turbine intake 4C (Swan et al.⁵¹). The forebay trash boom was in place for the first set of tests (five replicates) in early April, removed for the next two sets of tests (four replicates each) in late April, and then reinstalled for the remainder of the season. The raised operating gate was also tested.

As in 1984, FGE of Chinook salmon increased throughout the season. In the first three tests it averaged approximately 40% and was unchanged between the conditions with the trash boom out compared to trash boom in place. Over the first three sets of tests, FGE, however, averaged only about 67% of the TFGE. The Chinook

salmon FGE increased to an average of 69% through the end of the season and was 85% of the TFGE, with the exception of one test on 5 May when 40% spill occurred. On that date FGE dropped to 59%. For steelhead, FGE over the first three tests averaged 71% and was 85% of the TFGE. It averaged 89% for the remainder of the tests through the end of the season and was >90% of the TFGE, with the exception of 5 May. On that date FGE decreased to 69%, although this was 100% of the TFGE.

In 1985, no difference existed in FGE between conditions with the operating gate raised 6.1 or 18.8 m. Based on measurements of smoltification levels of Chinook salmon smolts sampled in mid-May from the gateway and fyke nets under the STS, it was theorized that changes in levels of smoltification in fish influenced the vertical distribution of fish, and this in turn could potentially explain why FGE was lower early in the season but increased later in the season (Giorgi et al., 1988). There was a good correlation between TFGE and FGE, but the difference between the two indicated that up to 35% of yearling Chinook salmon were still deflected below the STS.

Summary of Phase 4 Research and Problems Identified

The most startling result was the abysmal FGE measured for fish at the new Bonneville Dam Second Powerhouse. This was particularly puzzling because the fish passage facilities were based on seemingly successful designs and studies at McNary Dam. Yet, the two powerhouses do not have exactly the same turbine intake configurations. On hindsight, it seems clear that subtleties of the turbine intake, gateway, vertical barrier screen, and STS gateway/turbine intake configurations at McNary Dam were all particularly favorable to attaining acceptable FGE levels of yearling salmonid smolts; whereas, slight (or not so slight) changes in these configurations led to the particularly low FGE for Chinook salmon at the new Bonneville Dam Second Powerhouse.

While not as radical, the lower FGE measured at John Day Dam also did not match previous results attained at McNary Dam when it was operated to match a John Day Dam "configuration." It was therefore concluded that potentially each dam might have different FGE if measured with a "standard" STS and VBS. This complicated the efforts to develop guidance systems for fish because it appeared that all components of a bypass system would need to be tested specifically at each dam—even at those that appeared to have nearly the same turbine intake configurations.

Clearly, studies at lower Columbia River dams, with the exception of the 1981 studies at Bonneville Dam First Powerhouse, indicated STS would not extend far enough into turbine intakes to intercept a sufficient percentage of subyearling Chinook salmon to meet the minimum standard of 70%. Research at Lower Columbia River dams and at Lower Granite Dam also indicated that the amount of flow into the gateway affected the subsequent FGE of STS. Modifying porosity of STS and raising operating gates to increase flow into gateways generally also increased FGE; however, it also increased turbulence within gateways. The increased turbulence increased levels of descaling for fish guided into the gateway and also affected OPE which led to the conclusion that 30.5 cm diameter orifices were the minimum size needed to assure good OPE.

Testing also suggested that in most cases a BFVBS provided the best conditions for fish in gateways and improved OPE; particularly with the modified BFVBS that had the open screening near the orifices. It also seemed clear that to increase the percentage of fish intercepted by STS would require lower or longer STS. It was not clear what it would take to improve FGE for subyearling Chinook salmon because they migrated deeper through turbine intakes than yearling fish.

Not identified was why STS's were much less effective at intercepting

Walla Walla District by NOAA, Natl. Mar. Fish. Serv., Seattle, 33 p. [avail. at http://www.nwfsc.noaa.gov/assets/26/7303_07162012_093734_Swan.et.al.1985.pdf].

⁵¹Swan, G. A., R. F. Krema, and F. J. Ossiander. 1986. Continuing studies to improve and evaluate juvenile salmonid collection at Lower Granite Dam - 1985. Report to U.S. Army Corps of Engineers, Walla Walla District by NOAA, Natl. Mar. Fish. Serv., Seattle, 41 p. [avail. at https://www.nwfsc.noaa.gov/assets/26/7304_11142016_124843_Swan.et.al.1986-Smolt-collection-LGR.pdf].

subyearling Chinook salmon than other yearling salmon species and steelhead. It appeared that maximum FGE for subyearling Chinook salmon was approximately 65% even if the TFGE was near 100%. This compared to STS efficiency levels that often exceeded 80% for yearling migrants. Research in the next 10 yr was designed to address these issues.

Phase 5: Addressing Inadequacies of STS FGE, 1986–89

Lower Columbia River Dams

In 1986, more extensive testing of different options to increase FGE for subyearling chinook occurred at McNary Dam between 23 June and 1 August (Swan and Norman⁵²). The research evaluated a lowered STS, a raised operating gate, and the trash rack deflector used in the bar screen research (Fig. 11). Results were compared to simultaneous vertical distribution measurements of fish passing through the adjacent turbine intake. The results of the vertical distribution tests indicated that the average TFGE for different test conditions representing dusk to darkness periods (when 85% of fish pass turbines) ranged from 50% to 74%; with average FGE for different test conditions ranging from 21% to 61%.

The highest effectiveness rate (FGE/TFGE) during of these tests was 82%, and it occurred with a lowered STS, raised operating gate, and a trash rack deflector. The lowered STS by itself did not significantly improve guidance. The trash rack deflector increased FGE whether the operating gate was raised or not, and the one series that only compared FGE between daylight and darkness hours found much higher guidance during the former compared to the latter: 69% versus 26%.

The same test conditions were repeated in 1987, with the addition of

some limited testing on yearling migrants in the spring (Brege et al.⁵³). In the one set of spring evaluations with a raised operating gate, trash rack deflector, and lowered STS, FGE for yearling migrants ranged from 83% to 86%. The TFGE was 91%, however, it was only measured on one day, and the effectiveness of the STS (FGE/TFGE) was 87%. For tests with subyearling Chinook salmon, no statistically significant differences in FGE were detected among any of the test conditions. The absolute FGE varied widely from a high of 78% to a low of 7% during the testing period.

In 1988, due to concern about low FGE of subyearling Chinook salmon at upper river dams (see next section), it was decided to evaluate FGE at Bonneville Dam First Powerhouse for summer migrants since the initial studies, conducted in 1981, had occurred in April and May, and the FGE for subyearling Chinook salmon was near or exceeded the 70% goal. Between 6 and 27 July, study results indicated that FGE and TFGE for subyearling Chinook salmon averaged only 11% and 21%, respectively (Gessel et al.⁵⁴). The abysmally low results of both FGE and TFGE plus the ongoing installation of modifications for the construction of a new navigational lock dictated a need for additional guidance tests.

In 1989, testing was conducted at Bonneville Dam First Powerhouse throughout the spring and summer salmon outmigration to monitor FGE and TFGE (Gessel et al.⁵⁵). Results

for summer tests were similar to 1988 with FGE at times < 10% for subyearling Chinook salmon migrants. More disconcerting was that mean FGE and TFGE estimates for yearling Chinook salmon were much lower than expected, 42% and 70%, respectively, for a screen effectiveness of only 61%. The FGE was substantially lower than the 70% measured in 1981.

Lower Snake River Dams

In 1986, FGE studies were moved to Little Goose Dam to estimate FGE and determine the effectiveness of the STS because no direct measurements had been obtained with standard and raised operating gates, and also to determine if lower FGE occurred early in the season, as was seen at Lower Granite Dam the previous 2 yr (Swan et al.⁵⁶). As was found at Lower Granite Dam in 1985, smoltification indices for yearling Chinook salmon sampled from gatewells (guided fish) were significantly higher than those recovered from fyke nets (unguided fish) (Giorgi et al., 1988). The FGE, however, did not vary appreciably throughout the testing. With the operating gate raised 6.1 m, FGE averaged 74%, a significant ($P < 0.005$) 13% increase from the 61% measured with the operating gate in the normal stored position.

No significant difference was detected between FGE when the operating gate was raised from 6.1 m to 18.8 m. The estimated seasonal TFGE was 83% and based on FGE with the raised gate position, the seasonal effectiveness for yearling Chinook salmon was 88%. The average FGE for steelhead was 79%, which was 93% of the estimated TFGE. Descaling rates of year-

⁵³Brege, D. A., W. T. Norman, G. A. Swan, and J. G. Williams. 1988. Research at McNary Dam to improve fish guiding efficiency of yearling and subyearling Chinook salmon, 1987. Report to U.S. Army Corps of Engineers, Walla Walla District by NOAA, Natl. Mar. Fish. Serv., Seattle, 22 p. [avail. at https://www.nwfsc.noaa.gov/assets/26/8856_09162016_121950_Brege.et.al.1988b.pdf].

⁵⁴Gessel, M. H., B. H. Monk, D. A. Brege, and J. G. Williams. 1989. Fish guidance efficiency studies at Bonneville Dam First and Second powerhouses - 1988. Report to U.S. Army Corps of Engineers, Portland District by NOAA, Natl. Mar. Fish. Serv., Seattle, 36 p. [avail. at https://www.nwfsc.noaa.gov/assets/26/7002_05212012_085721_Gessel.et.al.1989a.pdf].

⁵⁵Gessel, M. H., D. A. Brege, B. H. Monk, and J. G. Williams. 1990. Continued studies to evaluate the juvenile bypass systems at Bonneville Dam -

1989. Report to U.S. Army Corps of Engineers, Portland District by NOAA, Natl. Mar. Fish. Serv., Seattle, 34 p. [avail. at https://www.nwfsc.noaa.gov/assets/26/7003_05212012_091315_Gessel.et.al.1990.pdf].

⁵⁶Swan, G. A., A. E. Giorgi, T. Coley, and W. T. Norman. 1987. Testing fish guidance efficiency of submersible traveling screens at Little Goose Dam: Is it affected by smoltification levels. Report to U.S. Army Corps of Engineers, Walla Walla District by NOAA, Natl. Mar. Fish. Serv., Seattle, 69 p. [avail. at https://www.nwfsc.noaa.gov/assets/26/7307_11142016_122800_Swan.et.al.1987-FGE-STSLGO-smolt.pdf].

⁵²Swan, G. A., and W. T. Norman. 1987. Research to improve subyearling Chinook salmon fish guidance efficiency at McNary Dam - 1986. Report to U.S. Army Corps of Engineers, Walla Walla District by NOAA, Natl. Mar. Fish. Serv., Seattle, 34 p. [avail. at https://www.nwfsc.noaa.gov/assets/26/7296_07122012_100641_Swan.and.Norman.1987.pdf].

ling Chinook salmon and steelhead were low, 2.1% and 0.7%, respectively.

In 1986 evaluations of FGE with STS were also made at Lower Monumental Dam (Ledgerwood et al.⁵⁷). As was found at Little Goose Dam, FGE for yearling Chinook salmon was higher with a raised operating gate compared to the standard position: 73% and 60%, respectively. The FGE was, however, only 81% of the estimated 90% TFGE. Of more concern were results for subyearling fall Chinook salmon released into the head of the Lower Monumental Dam reservoir from Lyons Ferry Hatchery. Similar to results found in the lower Columbia River, the mean FGE estimate in June was only 35% compared to an estimated 60% TFGE. This computes to an estimated STS efficiency of only 58%.

In 1987, FGE tests were repeated at Little Goose Dam (Ledgerwood et al.⁵⁸). The FGE in the 3rd week of April averaged 55% for yearling Chinook salmon and 70% for steelhead (small sample sizes). By the 1st week in May, FGE had increased to an average of 70% for Chinook salmon and 87% for steelhead.

In 1987, tests at Ice Harbor Dam were also conducted to determine levels of FGE with STS and vertical barrier screen designs used at Lower Granite and Little Goose Dams (Brege et al.⁵⁹). The STS was lowered, howev-

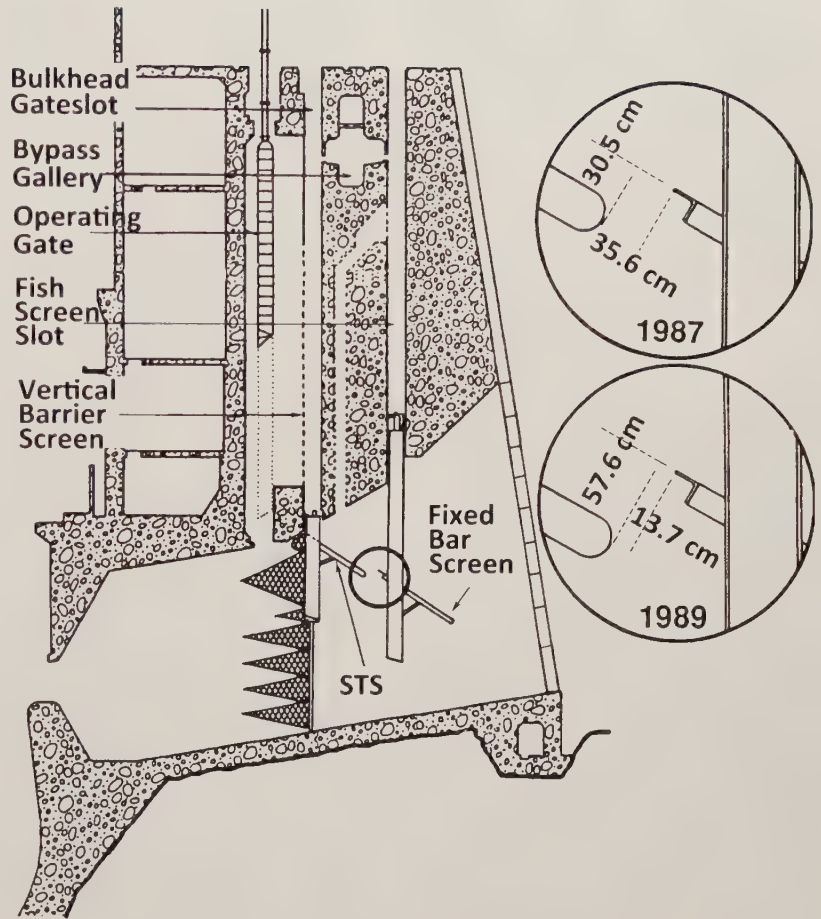


Figure 13.—Schematic of Lower Granite Dam showing configuration of installed submersible traveling screens (STS) in the bulkhead slot and fixed bar screens in the fish screen slot used in 1987 and 1989 to test a concept of a screen placed in the bulkhead gateslot that was double the length of STS evaluated.

⁵⁷Ledgerwood, R. D., G. A. Swan, and R. F. Krema. 1987. Fish guiding efficiency of submersible traveling screens at Lower Monumental Dam - 1986. Report to the Walla Walla District, U.S. Army Corps of Engineers by NOAA, Natl. Mar. Fish. Serv., Seattle, 33 p. [avail. at https://www.nwfsc.noaa.gov/assets/26/7115_07022012_094107_Ledgerwood.et.al.1987.pdf].

⁵⁸Ledgerwood, R. D., W. T. Norman, G. A. Swan, and J. G. Williams. 1988. Fish guiding efficiency of submersible traveling screens at Lower Granite and Little Goose Dams - 1987. Report to the Walla Walla District, U.S. Army Corps of Engineers by NOAA, Natl. Mar. Fish. Serv., Seattle, 34 p. [avail. at https://www.nwfsc.noaa.gov/assets/26/7116_07022012_095029_Ledgerwood.et.al.1988.pdf].

⁵⁹Brege, D. A., G. A. Swan, and J. G. Williams. 1988. Fish guiding efficiency studies at Ice Harbor Dam, 1987. Report to U.S. Army Corps of Engineers, Walla Walla District by NOAA, Natl. Mar. Fish. Serv., Seattle, 20 p. [avail. at https://www.nwfsc.noaa.gov/assets/26/8853_09142016_181850_Brege.et.al.1988.pdf].

er, 68 cm from the standard position. This configuration increased the throat opening and gap of the STS compared to earlier STS installations at most other projects. The operating gate was also raised 6 m. Results were some of the best seen to date at any dam. Mean FGE for yearling Chinook salmon and steelhead were 78% and 93%, respectively. The FGE values for steelhead were some of the highest ever recorded. The estimated TFGE's for yearling Chinook salmon and steelhead were also very high: 97% and 98%, respectively.

In 1987, research also returned to Lower Granite Dam (Ledgerwood et al.⁵⁸). To increase the percentage of flow intercepted, a deflector placed in

the fish screen slot in conjunction with STS was tested (Fig. 13). It was not considered as a possible permanent solution, but only as a means to evaluate a potentially longer STS. The FGE under control conditions for yearling Chinook salmon and steelhead ranged from 38% to 70% and from 64% to 83%, respectively. The higher values occurred later in the season and corresponded to higher levels of smoltification (Muir et al.⁶⁰). The combination of

⁶⁰Muir, W. D., A. E. Giorgi, W. S. Zaugg, W. W. Dickhoff, and B. R. Beckman. 1988. Behavior and physiology studies in relation to yearling Chinook salmon guidance at Lower Granite and Little Goose Dams, 1987. Report to U.S. Army Corps of Engineers, Walla Walla District by NOAA, Natl. Mar. Fish. Serv., Seattle, 47 p. [avail. at https://www.nwfsc.noaa.gov/assets/26/8853_09142016_181850_Brege.et.al.1988.pdf].

a 62 ft raised operating gate, the deflector, and lowered STS increased FGE approximately 15% in 15 of 17 tests compared to the condition without the deflector. However, significantly fewer fish entered the slot with the deflector than entered the slot without it.

This led to additional testing in 1989 (Swan et al.⁶¹). It was critically important to determine if the fish in 1987 had only moved sideways, to avoid the hydraulic conditions in the test turbine intake, to adjacent non-deflector intakes or if, potentially, fish might also choose to avoid the conditions created by the deflector and move either to an adjacent turbine or underneath the STS/deflector combination. Therefore, the repeat testing included deflectors in all three turbine intake slots of the test unit.

Additionally the configuration of the deflector/STS interface was altered (Fig. 13) to change the hydraulics in the area because just before the 1987 tests were conducted, USACE hydraulic modeling found that a large downward flow existed in the 35 cm gap between the end of the STS and the tip of the deflector. The results were that fish did not move laterally from the test turbine unit with bar screen deflectors to adjacent units without them.

For yearling Chinook salmon, FGE under control conditions (no bar screen deflector) ranged from 42% to 67% and with the bar screen deflector from 60% to 81%. Lower values generally occurred earlier in the season and corresponded with lower smoltification values (Muir et al.⁶²). Lower FGE also

occurred when large numbers of fish were recovered from gatewells. Results from paired treatment and control tests indicated that the deflectors significantly increased FGE by 15% and 7% for Chinook salmon and steelhead, respectively.

Phase 6: Research at McNary Dam to Develop Screen Alternatives to the STS, 1991–97

The USACE in 1990 began development of extended-length submersible traveling screens (ESTS) and extended-length submersible bar screens (ESBS) based on positive results from earlier studies at McNary and Lower Granite dams with STS and bar screen deflectors tested to simulate longer screens. The new screens were approximately double the length of the standard STS; approximately 12 m vs. 6 m. The ESBS were designed with wedge-wire screening material and a mechanical arm with a brush that rotated to the bottom of the screen and then advanced up the screen to remove impinged debris. Field research of these two types of screening systems and their effect on passage configurations in gatewells was mostly conducted at McNary Dam. Variants of screens that worked successfully at McNary Dam were then tested at other dams.

The initial testing of longer screens at McNary Dam began in 1991 (Brege et al.⁶³). Due to the size of the frames holding the screens, frames to hold fyke nets were put into the operating gateslot to recover fish not guided up the bulkhead gateslot and the gateway by the ESBS or ESTS (Fig. 5). Estimated flow that ESTS and ESBS would intercept in the turbine intakes

based on hydraulic model studies was applied to vertical distribution measurements of fish taken from fyke nets to attain an estimated TFGE. The extended length screens would also increase flow up the bulkhead gateslots.

To smooth flows within the gateway caused by increased flow with longer ESBS and ESTS, modified BFVBS (Fig. 8d) were redesigned for increased gateway flows. Results from fyke-net studies in late April indicated that the TFGE would exceed > 90% for yearling Chinook salmon, steelhead, and sockeye salmon, and in the third week of June > 90% for subyearling Chinook salmon. No vertical distribution measurements were conducted later in the summer.

In early tests, FGE for yearling Chinook salmon was 81% and 80% for ESTS and ESBS, respectively; however, unacceptably high descaling rates of 16–23% were observed with ESTS compared to descaling rates of STS of 7–8%. Descaling rates of ESBS averaged about 60% of the ESTS and were slightly higher than STS. Measurements of FGE were stopped while efforts were made to alter the ESTS in order to decrease descaling rates. No changes in operating gate position, screen angle, and/or flow through the turbine unit in combination with the extended screens significantly affected descaling rates; however, some baseline descaling likely occurred because of these factors.

Varying the porosity of the perforated plate on the ESTS from 45% to 34% lowered descaling rates of ESTS to ~12% and were similar to descaling rates measured in a control unit with STS. Tests of FGE that resumed in late May found FGE values for the ESTS and ESBS of 92% and 96% for steelhead, 93% and 92% for Coho salmon, 68% and 66% for sockeye salmon, and 81% and 73% for yearling Chinook salmon. The mean FGE for subyearling Chinook salmon was 64% for both the ESTS and ESBS, ranging from a high of 77% early in the season to 43% at the end. The mean was significantly higher than the 33% and 42% seasonal FGE means obtained in 1986

gov/assets/26/7194_07042012_131932_Muir.et.al.1988-rev.pdf].

⁶¹Swan, G. A., B. H. Monk, J. G. Williams, and B. P. Sandford. 1990. Fish guidance efficiency of submersible traveling screens at Lower Granite Dam - 1989. Report to U.S. Army Corps of Engineers, Walla Walla District by NOAA, Natl. Mar. Fish. Serv., Seattle, 51 p. [avail. at https://www.nwfsc.noaa.gov/assets/26/8962_11142016_121207_Swan.et.al.1990-FGE-STSLGR.pdf].

⁶²Muir, W. D., C. S. McCutcheon, A. E. Giorgi, Zaugg W. S., Hirtzel S. R., and Beckman B. R. 1990. An assessment of the relationship between smolt development and fish guiding efficiency at Lower Granite Dam, 1989. Report to U.S. Army Corps of Engineers, Walla Walla District by NOAA, Natl. Mar. Fish. Serv., Seattle, 19 p. [avail. at https://www.nwfsc.noaa.gov/assets/26/8855_09162016_111453_Brege.et.al.1992.pdf].

gov/assets/26/7199_07052012_095611_Muir.et.al.1990-rev.pdf].

⁶³Brege, D. A., Grabowski S. J., W. D. Muir, Hirtzel S. R., Mazur S. J., and B. P. Sandford. 1992. Studies to determine the effectiveness of extended traveling screens and extended bar screens at McNary Dam, 1991. Report to U.S. Army Corps of Engineers, Walla Walla District by NOAA, Natl. Mar. Fish. Serv., Seattle, 32 p. [avail. at https://www.nwfsc.noaa.gov/assets/26/8855_09162016_111453_Brege.et.al.1992.pdf].

and 1987, respectively, using STS. No tests of OPE were made in gateslots with extended-length screens.

In 1992, FGE tests were repeated, but only with ESBS because they caused less descaling of guided fish in 1991 (McComas et al.⁶⁴). The ESTS was used only for descaling tests while a redesigned, more streamlined ESTS was being developed for prototype testing in 1993. To potentially increase FGE from values obtained in 1991, new test conditions were evaluated. They included changes in screen angles, height of screens below gatewells, and different perforated plate porosities in combination with different operating gate elevations. Results again indicated that FGE of ESBS for yearling and subyearling Chinook salmon were significantly better than the STS during the spring and summer migration: 80 and 53% for the yearling and subyearling Chinook salmon, respectively, compared to 61 and 30% for the STS.

Descaling rates on yearling Chinook salmon with ESTS were, however, often more than double the descaling rates with STS. Lowering ESBS 90 cm below the standard elevation resulted in lower FGE because fish passed through the gap between the turbine intake ceiling and the screen. Tests with a 60 cm lowered screen were limited in number and did not appear to provide benefit over the standard elevation. The ESBS at standard screen elevation, set at a 55° angle, with 30% perforated plate porosity, and a partially raised operating gate produced descaling rates similar to those with the STS for yearling and subyearling Chinook salmon: 12.7% vs. 10.9% and 6.6% vs. 5.1%, respectively. These rates were lower than descaling rates with other ESBS configurations tested.

No tests of OPE were made in gateslots with ESBS.

In 1993, the newly designed ESTS and the previously designed ESBS were again tested at McNary Dam (McComas et al.⁶⁵). The old ESTS had porosities of 25% and 34%, while the new ESTS had porosity of 36%. The designs were set to provide an approach velocity at the screen of 0.75 m/s and a velocity at the throat of 2.7 m/s. When all 20 nights of tests were combined for each screen type without regard to whether the operating gate was partially raised or removed, mean FGE for ESTS were significantly higher than for ESBS for yearling Chinook salmon, steelhead, and sockeye salmon: 88%, 93%, and 85% versus 81%, 91%, and 73%, respectively.

For yearling Chinook salmon, no significant difference in FGE or descaling was detected based upon whether the operating gate was partially raised or removed entirely. No significant differences in mean descaling rates of yearling Chinook salmon existed among ESBS, ESTS, or STS. The FGE for subyearling Chinook salmon was significantly higher with ESTS (67%) than with ESBS (52%) when both were used with a partially raised operating gate; however, the FGE for ESTS (67%) was not significantly different compared to ESBS (59%) with no operating gate. The descaling rate for ESTS (12.2%) was significantly higher for subyearling Chinook salmon than all other operating gate/screen type combinations, including the STS. There were no significant differences among any of the other treatments.

In 1994, more effort was directed at understanding the effects of bypass system configurations on levels of fish descaling. Studies over the past decade had found that raising operating gates generally increased FGE for STS, however, at the expense of increased

descaling and/or decreased effectiveness of orifices to pass fish out of the gatewell. The recent FGE studies with ESTS and ESBS also increased flows into gatewells and in some cases led to higher rates of descaling. While levels of descaling were sometimes not much different between STS and ESTS or ESBS, the overall levels of descaling were often higher than seen in gatewells with no guidance screens and a stored operating gate.

Two new vertical barrier screen configurations designated VBS1 and VBS2 were tested to determine if they would decrease descaling. Rather than polyester mesh, the upstream surfaces were composed of No. 69 industry-standard profile wire, composed of 1.8 mm wedge-wire strands with 3.2 mm spaces between strands. This created an overall surface porosity of 62%. On the downstream surface, vertically variable perforated plate panels were used to disperse flows within the gatewell more evenly over the entire VBS surface. Outlet flow control louvers were installed to control flow through the VBS-gatewell environment and flow deflector bases were used on both test VBS systems to smooth flows during transition into the gatewell. These VBS were compared to conditions with the modified BFVBS with and without a flow deflector (McComas et al.⁶⁶). The configuration of the new VBS surface—solid panels and open areas—were the same as used with modified BFVBS.

Results of evaluations found that mean descaling values for yearling and subyearling Chinook salmon were not significantly different among VBS1 and VBS2 with ESBS and a control modified BFVBS used with a STS. Yearling Chinook salmon FGE with ESBS in conjunction with VBS2 was, however, significantly higher than with VBS1: 89% vs. 85%, respectively. No

⁶⁴McComas, R. L., D. A. Brege, W. D. Muir, B. P. Sandford, and D. B. Dey. 1993. Studies to determine the effectiveness of extended-length submersible bar screens at McNary Dam, 1992. Report to U.S. Army Corps of Engineers, Walla Walla District by NOAA, Natl. Mar. Fish. Serv., Seattle, 92 p. [avail. at https://www.nwfsc.noaa.gov/assets/26/6733_12302010_123027_McComas.et.al.1993-rev.pdf].

⁶⁵McComas, R. L., B. P. Sandford, and D. B. Dey. 1994. Studies to evaluate the effectiveness of extended-length screens at McNary Dam, 1993. Report to U.S. Army Corps of Engineers, Walla Walla District by NOAA, Natl. Mar. Fish. Serv., Seattle, 109 p. [avail. at https://www.nwfsc.noaa.gov/assets/26/6734_12302010_123503_McComas.et.al.1994-rev.pdf].

⁶⁶McComas, R. L., B. P. Sandford, and D. B. Dey. 1995. Vertical barrier screen studies at McNary Dam, 1994. Report to U.S. Army Corps of Engineers, Walla Walla District by NOAA, Natl. Mar. Fish. Serv., Seattle, 101 p. [avail. at https://www.nwfsc.noaa.gov/assets/26/6735_12302010_124330_McComas.et.al.1995-rev.pdf].

significant differences in mean descaling values existed between polyester mesh and profile wire VBS1 surface materials for yearling and subyearling Chinook salmon.

In 1995, efforts were again primarily directed at evaluating descaling rates of yearling and subyearling Chinook salmon (McComas et al.⁶⁷). Tests were conducted on two new alternative beam extensions with newly designed VBS systems and an ESBS with an inlet flow vane. The two new configurations were compared against the control condition of the now standard McNary Dam configuration of STS, modified BFBVS, and raised operating gate. Additionally, OPE was tested under the conditions that occurred in the gateway with these particular screen and VBS conditions.

The control condition had significantly higher yearling Chinook salmon descaling rates than for either beam extension treatment used with ESBS and inlet flow vanes. No significant difference in mean descaling values was found for subyearling chinook among the test and control conditions. There was no significant difference in mean descaling values for yearling and subyearling Chinook between either of the test conditions. The OPE averaged 74%, 92%, 93%, and 87% for yearling Chinook salmon, steelhead, coho salmon, and sockeye salmon, respectively, in the gateway using ESBS and VBS2 with an inlet flow vane. No significant difference existed between OPE values for the north and south orifices. Differences in mean descaling values between gateway and orifice traps for yearling and subyearling Chinook salmon were not significant.

Based on research and testing of screening systems at McNary Dam from 1991 to 1995, ESBS with a flow vane, a modified VBS, and the operating gate removed provided the highest

level of FGE. As a result, in 1996 the USACE installed ESBS in all turbine intake units at the dam. Subsequent to their installation, a reevaluation of the emergency turbine safety procedures found that it was necessary to have the operating gates remain in the gateslots instead of being removed entirely from the slots (the operating condition for which the ESBS guidance system was developed). Recognizing that the operating gate remaining in the gateslot would change the hydraulic conditions within the gateway, the USACE conducted hydraulic modelling on a partially raised operating gate.

The results led to changing the VBS. The effect of the change was evaluated in 1997 along with how different levels of turbine discharge and changes of flow into the gateway from an outlet flow-control device would affect levels of OPE and fish descaling (Brege et al.⁶⁸). Turbine discharge was evaluated because during the juvenile fish passage season turbines are supposed to operate within 1% of peak efficiency. At McNary Dam, that translates into turbines producing essentially between 60–75 MW of power. The difference between the lower and upper bounds equates to turbine discharge of between approximately 224 and 348 m³/s, depending on head.

Higher turbine discharges cause higher water velocities within turbine intakes and greater flows into the gateway with resultant higher velocity. Results of studies found that mean OPE for yearling and subyearling Chinook salmon was significantly higher at the 75 MW load than at the 60 MW load, but also descaling rates were significantly higher. With the flow control device limiting the flow into the gateway, OPE was lower, but descaling rates were also lower.

Phase 6: Part Two, System-wide tests of ESTS and/or ESBS

In 1993, ESTS and ESBS were tested at Little Goose Dam (Gessel et al.⁶⁹). Because Little Goose Dam has higher intake velocities than McNary Dam, testing of screens with a lower porosity was needed to limit approach velocities at the screen to the required 0.75 m/s. In 1993, the ESTS and ESBS were tested with porosities of 22%, 25%, and 28%. Initial testing found that none of the porosities created unacceptable levels of descaling and thus, further testing was allowed. Constraints resulting from the listing of Snake River sockeye and spring/summer Chinook salmon under the U.S. Endangered Species Act influenced the FGE and descaling evaluations because it limited the number of fish that researchers could handle and the potential number that could be collected in fyke nets.

Because of the unusually high ratios of wild to hatchery yearling Chinook salmon, high river flows, and a delay in the outmigration of approximately 2 weeks, only a portion of the desired number of FGE tests were conducted. Test results of ESTS and ESBS had similar values and the combined mean FGE was 85% and 90% for yearling Chinook salmon and steelhead, respectively, for the tests successfully completed. The STS had a mean FGE of 74% and 95% for yearling Chinook salmon and steelhead, respectively. The mean rate of descaling for yearling Chinook salmon was significantly higher with ESTS (12%) than with ESBS (9%) and STS (7%). No significant difference in mean descaling existed between the ESBS and STS. Descaling rates for steelhead ranged from ~5% prior to mid-May, 15% in late May, and 25% by early June,

⁶⁷McComas, R. L., B. P. Sandford, and D. B. Dey. 1997. Descaling and orifice passage efficiency studies at McNary Dam, 1995. Report to U.S. Army Corps of Engineers, Walla Walla District by NOAA, Natl. Mar. Fish. Serv., Seattle, 35 p. [avail. at https://www.nwfsc.noaa.gov/assets/26/5424_12122016_150047_McComas.et.al.1997-OPE-McNary-95.pdf].

⁶⁸Brege, D. A., Absolon R. F., B. P. Sandford, and D. B. Dey. 1998. Studies to evaluate the effectiveness of vertical barrier screens and outlet flow-control devices at McNary Dam, 1997. Report to U.S. Army Corps of Engineers, Walla Walla District by NOAA, Natl. Mar. Fish. Serv., Seattle, 37 p. [avail. at https://www.nwfsc.noaa.gov/assets/26/6732_12202010_174807_Brege.et.al.1998.pdf].

⁶⁹Gessel, M. H., B. P. Sandford, and D. B. Dey. 1994. Studies to evaluate the effectiveness of extended length screens at Little Goose Dam, 1993. Report to U.S. Army Corps of Engineers, Walla Walla District by NOAA, Natl. Mar. Fish. Serv., Seattle, 42 p. [avail. at https://www.nwfsc.noaa.gov/assets/26/7005_05212012_093420_Gessel.et.al.1994.pdf].

but, no significant difference existed among the screen types.

In 1994, FGE and descaling evaluations were repeated at Little Goose Dam because of the limited testing that occurred the previous year (Gessel et al.⁷⁰). However, only 10 FGE evaluations rather than the 20 originally planned were conducted and only ESBS were tested with fyke nets because of concern about effects on listed wild fish. The ESBS porosities tested were 25% and 28%. Descaling evaluations were made for STS, ESBS, and one ESTS. None of the descaling results for the two extended-length screen types or the STS were statistically different for yearling Chinook salmon or steelhead. Descaling rates averaged 7.6% and 5.4%, respectively. For yearling Chinook salmon, no statistical difference existed in FGE between the two porosities and the combined mean FGE was 76%. For steelhead, the mean FGE was significantly higher (92% vs. 88%) for the 25% vs. 28% porosity ESBS.

In 1993 and 1994, tests with ESBS and ESTS were also conducted at The Dalles Dam (Brege et al.⁷¹; Absolon et al.⁷²). In 1993, ESBS, ESTS, and STS were tested in three of the lower-flow capacity turbine units installed originally in 1960 on the west end of the powerhouse, and in 1994 three of the higher-flow capacity turbines installed in 1973 on the east end of the power-

house. In both years, the porosity of the tested STS was the standard 48%. In 1993, the porosity of ESBS and ESTS ranged from 45% to 55% and from 49% to 54%, respectively, and in 1994 from 25% to 35% and from 39% to 44%, respectively.

In 1993, FGE for yearling Chinook salmon was 73%, 60%, and 44% for ESBS, ESTS, and STS, respectively, for steelhead 83%, 67%, and 62%, respectively, and for subyearling Chinook salmon 59%, 51%, and 23%, respectively. Descaling rates were not significantly different between any of the screens and averaged 4.6%. In 1994, mean FGE for ESBS was 69% and ESTS 65%, but were not significantly different for yearling Chinook salmon. Although mean descaling rates were low for all three screen types, the 3.2% for ESBS and 3.4% for ESTS were significantly higher than the 0% STS for yearling Chinook salmon. For subyearling Chinook salmon, mean FGE of 54% for ESBS was significantly higher than 47% for ESTS. For subyearling Chinook salmon, ESTS had a significantly higher mean descaling rate (3.3%) than ESBS (1.8%) or STS (0.7%). There was no significant difference between the descaling rates of ESBS and STS. To help assess the results from the 1993 and 1994 studies, the horizontal distribution of fish passing The Dalles Dam was made in 1994. Results indicated that juvenile salmonid passage was considerably higher in the west turbine units of the powerhouse than in either the center or east units.

In 1995, studies were conducted at Lower Granite Dam to determine if good OPE conditions would exist with the use of the VBS and ESBS configuration determined to provide the best conditions at McNary Dam in 1994 (Monk et al.⁷³). Evaluations

found that when this set up was used at Lower Granite Dam, OPE was over 90% for yearling Chinook salmon and steelhead. There was no statistically significant difference in OPE between the north and south orifices. Descaling with the test guidance devices was < 1% for yearling Chinook salmon and < 4% for steelhead, and these values were not significantly different from descaling measured with STS during the same period. During three OPE tests using orifice traps, approximately 50% of the daily juvenile salmonid passage occurred between 2000 h and 2400 h.

Bonneville Dam Conundrum

At the new Bonneville Dam Second Powerhouse, none of the research throughout the mid- to late 1980's materially improved FGE (Gessel et al., 1991). No clear resolutions to the problem with low FGE were identifiable. At Bonneville Dam First Powerhouse, the evaluations during 1988–89 found lower than expected FGE compared to the initially favorable levels observed with prototype STS in 1981. The initial speculation was that it resulted from changes in the forebay of the powerhouse related to construction of a new navigational lock at the dam site.

In 1991, renewed FGE testing began across the entire powerhouse, with additional testing of a raised operating gate. Results indicated that during the early part of the spring outmigration, FGE for yearling Chinook salmon varied within and among turbine units and ranged from 19% to 67%; all estimates below the minimum 70% target level (Monk et al.⁷⁴). Tests did find that raising the operating gate in Unit 8 significantly increased FGE for yearling Chinook salmon, from 30% to 50%.

⁷⁰Gessel, M. H., B. P. Sandford, and D. B. Dey. 1995. Studies to evaluate the effectiveness of extended-length screens at Little Goose Dam, 1994. Report to U.S. Army Corps of Engineers, Walla Walla District by NOAA, Natl. Mar. Fish. Serv., Seattle, 33 p. [avail. at https://www.nwfsc.noaa.gov/assets/26/7006_05212012_093752_Gessel.et.al.1995.pdf].

⁷¹Brege, D. A., R. F. Absolon, B. P. Sandford, and D. B. Dey. 1994. Studies to evaluate the effectiveness of extended-length screens at The Dalles Dam, 1993. Report to U.S. Army Corps of Engineers, Portland District by NOAA, Natl. Mar. Fish. Serv., Seattle, 72 p. [avail. at https://www.nwfsc.noaa.gov/assets/26/5598_09162016_115339_Brege.et.al.1994.pdf].

⁷²Absolon, R. F., D. A. Brege, B. P. Sandford, and D. B. Dey. 1995. Studies to evaluate the effectiveness of extended-length screens at The Dalles Dam, 1994. Report to U.S. Army Corps of Engineers, Portland District by NOAA, Natl. Mar. Fish. Serv., Seattle, 69 p. [avail. at https://www.nwfsc.noaa.gov/assets/26/5599_08082014_120556_Absolon.et.al.1995.pdf].

⁷³Monk, B. H., B. P. Sandford, and D. B. Dey. 1997. Evaluation of orifice passage efficiency and descaling with an extended-bar screen, new vertical barrier screen, and inlet flow vane at Lower Granite Dam, 1995. Report to U.S. Army Corps of Engineers, Walla Walla District by NOAA, Natl. Mar. Fish. Serv., Seattle, 25 p. [avail. at https://www.nwfsc.noaa.gov/assets/26/6761_08022011_131503_Monk.et.al.1997-rev.pdf].

⁷⁴Monk, B. H., Varney G. E., and Grabowski S. J. 1992. Continuing studies to evaluate and improve submersible traveling screens for fish guidance at Bonneville Dam First Powerhouse–1991. Report to U.S. Army Corps of Engineers, Portland District by NOAA, Natl. Mar. Fish. Serv., Seattle, 20 p. [avail. at https://www.nwfsc.noaa.gov/assets/26/7178_07042012_104908_Monk.et.al.1992b-rev.pdf].

Additional testing occurred in 1992 with a lowered STS, but results did not improve over those found with the raised operating gate in 1991 (Monk et al.⁷⁵). Also, contrary to results obtained in 1991, raising the operating gate did not significantly improve FGE for yearling Chinook salmon; however, it did significantly increase FGE for subyearling Chinook salmon, Coho salmon, and steelhead although again FGE for several blocks of tests did not reach the minimum goal of 70%. Additionally, both FGE and TFGE for subyearling Chinook showed a progressive decline throughout the field season.

Efforts were then again directed at the Bonneville Second Powerhouse. Studies in the 1980's had all been conducted in Turbine Unit 12, but recommendations at the time to increase FGE at the powerhouse were not implemented and tested. In 1993, tests of FGE in south, middle, and north turbine units, under full and partial powerhouse operation for spring and summer migrations were conducted to evaluate modifications to the powerhouse proposed previously—alternating turbine intake extensions (TIE) between gateslots, lowered STS's, and streamlined trash racks (Monk et al.⁷⁶). Results were still disappointing.

For yearling Chinook salmon during the spring migration, with 4–6 turbines operating, mean FGE was 44% and with eight turbines it was 50%. Over the same turbine operating conditions, the range of FGE for all other species ranged from only 35% to 60%.

Turbine operations influenced where

fish passed the dam. Results indicated that the fewer the number of turbines operating, the greater the percentage of fish that entered a gateslot without a TIE. During the summer migration, with four or six turbine units in operation, FGE for subyearling Chinook salmon ranged from 23% to 42% (non-TIE slots) and was significantly higher with six units in operation than with four. In 1994, tests were repeated with a more limited turbine operation and FGE was measured only in non-TIE turbine intakes (Monk et al.⁷⁷). Results were essentially the same as in 1993.

A complete review of all studies associated with FGE at the Bonneville Second Powerhouse was completed in 1999 (Monk et al.⁷⁸). While it provided some possible explanations for the poor FGE levels that existed at the dam, because precise data on near-field behavior of migrating fish arriving at the powerhouse and how fish interacted with the hydraulic conditions they encountered was not known, the review could not attribute the low guidance to any particular factors at the dam.

Finally, to address low FGE found at Bonneville First Powerhouse, ESBS with raised operating gates were tested in 1998, along with assessing how these conditions might potentially affect OPE and descaling (Monk et al.⁷⁹). In the spring, FGE for yearling and subyearling Chinook salmon aver-

aged 72% and 67%, respectively. For steelhead, coho salmon, and sockeye salmon FGE averaged 85%, 80%, and 51%, respectively. During the same time period, in a comparison between the test conditions and a control STS with stored operating gate, OPE for yearling Chinook salmon was 90% and 80%, respectively.

A significant difference existed between the descaling rates of 10% for spring Chinook salmon with the ESBS test conditions compared to 8% for the standard STS condition. No significant differences in descaling rates existed between the two conditions for subyearling Chinook salmon, steelhead, coho salmon, or sockeye salmon. During summer evaluations of subyearling Chinook salmon, FGE averaged 55% from 22 to 27 June, but dropped to 27% from 29 June to 17 July. The values were much higher than the average FGE of 11% and 4%, respectively, during similar periods in 1988 and 1989. During the summer migration, OPE averaged 97% with the ESBS and 98% with the standard STS and descaling values averaged 3% with the ESBS and 2% with the standard STS.

Phase 7: Implementation

Nearly all field research to test and develop screening systems for turbine intakes or orifices in gatewells was conducted by BCF-NMFS. When research results indicated configurations of screens and/or orifices would potentially increase the percentage of fish that would pass a non-turbine route, the information was considered by the USACE and fishery agencies. Recommendations/decisions were made about implementing those that appeared promising. The USACE would then include costs in budgets submitted to Congress.

Installation of systems and/or parts to systems began in 1968. The turbine intake screening systems and orifice combinations installed at USACE dams on the Lower Snake and Colum-

⁷⁵Monk, B. H., Ross J. A., B. P. Sandford, and D. B. Dey. 1993. Continuing studies to measure and improve fish guidance efficiency of submersible traveling screens at Bonneville Dam First Powerhouse, 1992. Report to U.S. Army Corps of Engineers, Portland District by NOAA, Natl. Mar. Fish. Serv., Seattle, 32 p. [avail. at https://www.nwfsc.noaa.gov/assets/26/6182_11072016_143026_Monk.et.al.1993-FGE-STSS.pdf].

⁷⁶Monk, B. H., B. P. Sandford, and D. B. Dey. 1994. Evaluation of fish guidance efficiency of submersible traveling screens and other modifications at Bonneville Dam Second Powerhouse, 1993. Report to U.S. Army Corps of Engineers, Portland District by NOAA, Natl. Mar. Fish. Serv., Seattle, 48 p. [avail. at https://www.nwfsc.noaa.gov/assets/26/6760_08022011_130754_Monk.et.al.1994-rev.pdf].

⁷⁷Monk, B. H., B. P. Sandford, and D. B. Dey. 1995. Evaluation of fish guidance efficiency of submersible traveling screens and other modifications at Bonneville Dam Second Powerhouse, 1994. Report to U.S. Army Corps of Engineers, Portland District by NOAA, Natl. Mar. Fish. Serv., Seattle, 29 p. [avail. at https://www.nwfsc.noaa.gov/assets/26/7180_07042012_110617_Monk.et.al.1995-rev.pdf].

⁷⁸Monk, B. H., M. H. Gessel, and Ferguson J. W. 1999. An evaluation of the biological database for improving fish guidance efficiency at Bonneville Dam Second Powerhouse. Report to U.S. Army Corps of Engineers, Portland District by NOAA, Natl. Mar. Fish. Serv., Seattle, 62 p. [avail. at https://www.nwfsc.noaa.gov/assets/26/6762_08022011_132022_Monk.et.al.1999-rev.pdf].

⁷⁹Monk, B. H., B. P. Sandford, and D. B. Dey. 1999. Evaluation of extended-length submersible bar screens at Bonneville Dam First Powerhouse, 1998. Report to U.S. Army Corps of Engineers, Portland District by NOAA, Natl. Mar. Fish. Serv., Seattle, 48 p. [avail. at https://www.nwfsc.noaa.gov/assets/26/6582_07202010_121023_Monk.et.al.1999-rev.pdf].

bia Rivers were essentially completed in 1997 (Table 1). Complete turbine intake screening systems or retrofits to ESBS from STS, after taking into account the expected decrease in turbine mortality that would occur for populations of fish passing a dam, were not installed at all powerhouses.

A few small changes to installed systems were made after 1997. The original ESBS had perforated plates attached to the downstream side to balance flow so that juvenile salmon were not impinged on the face of the guiding device. The perforated plate was bolted or welded to the framework that supports the ESBS. Within a year of use, in some instances, vibration caused by flow through the perforated plate caused the bolts or welds to break. Hydraulic model studies, conducted at the Iowa Institute of Hydraulic Research, indicated that changing the perforated plate to one that had 30° full-chamfered perforations would dampen the vibration.

In 1999, research was conducted at Lower Granite Dam in the spring and McNary Dam in the summer to evaluate such a perforated plate design against the original design to determine if it would affect condition of fish diverted by ESBS into the bulkhead slot gateway (Gessel et al.⁸⁰). The condition of fish guided by ESBS with the new design was also observed at Little Goose Dam. Results from the comparative studies found that the changed perforation did not increase descaling and/or injury to the fish compared to the standard perforated plate. At Little Goose Dam, the long-term (19 h) descaling for yearling Chinook salmon was significantly lower with the chamfered plate, indicating that the new design might have also decreased turbulence in the gateway.

⁸⁰Gessel, M. H., B. H. Monk, B. P. Sandford, and J. W. Ferguson. 2000. Evaluation of a chamfered perforated plate for extended-length bar screens at Little Goose and McNary dams, 1999. Report to U.S. Army Corps of Engineers, Walla Walla District by NOAA, Natl. Mar. Fish. Serv., Seattle, 23 p. [avail. at https://www.nwfsc.noaa.gov/assets/26/6553_07122010_100734_Gessel_et.al.2000a-rev.pdf].

Table 1.—Installation of turbine intake screens, orifices, and vertical barrier screens (VBS) at USACE operated dams on the Lower Snake and Columbia River dams, 1969–97.

Dam	Screen type (no.)	Year installed	Orifice diameter (cm) [no./gateway]	Year installed	VBS type	Year installed
Bonneville First	None			1969	None	
Bonneville Second	STS	1982	30.5 (2)	1982	BFVBS	
The Dalles	None		15.2 (1)	1969	None	
John Day			15.2 (1)	1969	VBS	1985
John Day	STS	1985–86	35.6 (1)	1985–86	MBFVBS	1985–86
McNary	STS (3)	1978	15.2 (2)	1968–69	VBS (9)	1978
McNary	STS (39)	1981	30.5 (2)	1981	VBS (33)	1979
McNary	ESBS	1997			MBFVBS (42)	1997
Ice Harbor	STS (24)	1992–93	15.2 (1)	1970	MBFVBS	1992
Ice Harbor			35.6 (2)	1992–93	MBFVBS	1992
Lower Monumental	STS (18)	1992	(24) 15.2 (1)	1969		
Lower Monumental			(24) 30.5 (2)	1991		
Little Goose	STS (6) + (13)	1973 & 1981	15.2 (1)	1969	VBS (9)	1973 & 1981
Little Goose	ESBS (18)	1997	30.5 (1)	1984	MBFVBS2	1997
Lower Granite	STS (9)	1975–76	20.3 (2)	1975	VBS (3) & (6)	1975–76
Lower Granite	STS (18)	1978	25.4 (2)	1990	MBFVBS	1976
Lower Granite	ESBS (18)	1997			MBFVBS2	1997

Discussion

The research to develop effective turbine intake screens to guide/divert juvenile salmon away from turbines and into gateways, vertical barrier screens to hold fish within gateways, and orifices to provide a safe passage route from gateways took much longer than initially envisioned in the 1960's. We ascribe this to the following two general factors.

First, throughout nearly the entire 30-y period of testing, biologists lacked detailed knowledge on how juvenile salmonids responded to variations in flow and velocity. Without this, they could not provide engineers the specific criteria needed to design effective screens and orifices. Additionally, engineers did not know how equipment would affect hydraulic conditions on a scale fine enough so that it could be matched with results from biological testing. As a result, although most tests in the first couple of decades were conducted based on the best intuition about how fish would respond to hydraulic conditions they encountered, when a piece of test equipment didn't work as presumed, it was often unclear as to why.

Second, the period for successful testing of research equipment was limited to times when migrant fish were in the river. For yearling migrants, this generally limited testing to the months of April and May. For subyearling mi-

grants, tests were generally limited to a 60-day window from late June into late August. These limited time periods strained the ability to conduct field research with sufficient replication to meet good experimental design for more than a few different test conditions per year. This also made it difficult to compensate for late delivery or breakdown of equipment. Finally, because of test equipment size, in cases where it was clear early in a testing season that results were not nearly as good as expected, it was generally not possible to make any alterations to the equipment in time to re-test within a migration year.

As a consequence of these two major factors, annual incremental increases in knowledge and/or increases in FGE or OPE with concomitant low levels of descaling were often small to none—even after months of planning, design, and construction of new test equipment based on the best knowledge of dozens of biologists and engineers working to develop the new equipment to test. Most discouragingly, sometimes test equipment worked well at one site or under one particular condition, which then implied that a bypass solution was found. Subsequently, tests were scheduled at another dam, but similar positive results were not obtained. The most glaring example occurred at Bonneville Dam Second Powerhouse where tens of millions of dollars spent on fish passage

facilities failed to meet passage criteria, yet they were designed based on what were considered good FGE and passage conditions at McNary Dam.

Initially, field studies attempted to determine FGE or OPE for all salmonid species, but often the variety of test conditions plus the ever changing juvenile salmonid population made this impossible. For any one test, it could often lead to over-sampling of some species and under sampling others. The former led to unnecessary handling and incidental mortality, and the latter, too few fish to provide sufficient statistical precision. Thus, testing was focused on yearling spring Chinook salmon in the spring and subyearling Chinook salmon in the summer.

Data for steelhead, coho salmon, and sockeye salmon were collected and evaluated as available. Fishery agencies and tribes also began limiting field research to decrease the number of fish handled in dip nets and sacrificed in fyke nets. The fyke nets used to capture nonguided fish resulted in 100% mortality. To decrease fyke-net mortality, testing protocol was changed to use only the center row of nets. This change was based on analyses of initial FGE field research with complete complements of fyke nets which found multiplying by 3 just the number of fish recovered from the center column of nets provided a reasonable estimate of the total number of nonguided fish. Further, by the mid-1980's, researchers set a target number of 250 total fish to collect for each replicate. This number included fish dipped from the gateway plus those recovered from fyke nets.

For statistical purposes, a minimum of three replicates was needed for each test configuration. The Federal listing of Snake River sockeye salmon (NMFS⁸¹) under the U.S. Endangered Species Act (ESA) in fall 1991 and

Snake River yearling and subyearling Chinook salmon (NMFS⁸²) in spring 1992 placed additional onus on developing better means to divert fish away from turbines. Yet, at times, all research to obtain needed information was stopped when large percentages of wild fish were in the migration.

The listings led to consideration of trade-offs between sampling methodologies to attain FGE estimates and mortalities to test fish. Nonetheless, because the extended screens had a large impact on turbine intake flow, and preliminary analyses from research at McNary Dam indicated that the center row of nets would underestimate the number of nonguided fish, studies that evaluated FGE of extended screens used a complete array of fyke nets.

For decades, biologists were fairly certain that successful FGE and OPE, or lack thereof, were related to behavior of fish, yet the degree that behavior played in attaining successful results compared to changes in physical structures or conditions at dams was not clearly known. A review of factors effecting FGE was conducted in the mid-1990's in an effort to try to understand why researchers found such variable FGE over the previous decades (Williams et al.⁸³).

Fish behavior appeared to play a large role. The review outlined laboratory studies that provided some of the first evidence that migrating juvenile Chinook salmon smolts actively avoided areas with decreasing water velocity, such as occurs upstream of guidance screens in turbine intakes. Enders et al. (2012) subsequently found that juvenile Chinook salmon

also actively avoided rapidly increasing water velocity conditions. Most interestingly, the threshold change in water velocity that elicits avoidance response has a similar magnitude for increasing and decreasing water velocity conditions.

On hindsight, while the specifics of water velocity/acceleration were not specifically known, it certainly appears that they correlated with general differences in FGE and OPE attained in studies. With respect to effects of screens in turbine intakes, configuration of the intakes appeared to influence FGE. At the four oldest dams with curved ceiling intakes, in general, higher FGE has been obtained than at the five newer powerhouses with a relatively straight turbine intake ceiling (Fig. 3.) We think the higher FGE resulted from more favorable conditions as fish approached screens. The flow into turbine intakes at the older dams accelerates more gradually because of the longer curved ceilings.

We conjecture that a higher percentage of fish remained higher in the water column before approaching the decelerating water conditions caused by screens and thus, more were guided or deflected into the gateway. In contrast, we think at dams with straight ceiling intakes, water velocity increased more rapidly farther upstream than at intakes with curved ceilings. As a result, a higher percentage of fish detected decreasing water velocities farther upstream of STS and lower FGE resulted when fish actively moved to avoid the decreasing water velocity conditions caused by screens.

The conditions in the gateway and the size of the orifice influence the OPE. The research on orifices found that sufficient submergence and head to create water velocities of > 3 m/sec were required to obtain high OPE values. This velocity exceeds the swimming ability of juvenile salmonid smolts. It suggests that flow into orifices traps fish.

All orifices at the same submergence and head have the same increase in water acceleration, but the area of acceleration is more abrupt in orifices with

⁸¹NMFS. 1991. Endangered and threatened species; endangered status for Snake River sockeye salmon. Federal Register 56: No. 224 (November 20, 1991), p. 58619-58624. U.S. Dep. Commer., NOAA, Washington, D.C. [avail. at http://www.westcoast.fisheries.noaa.gov/protected_species/salmon_steelhead/salmon_and_steelhead_listings/sockeye/sockeye_salmon_federal_register_notices.html].

⁸²NMFS. 1992. Threatened status of Snake River spring/summer Chinook salmon, threatened status for Snake River fall Chinook salmon. Federal Register 57: No. 78 (April 22, 1992), p. 14653-14663. U.S. Dep. Commer., NOAA, Washington, D.C. [avail. at <http://www.westcoast.fisheries.noaa.gov/publications/frn/1992/57fr14653.pdf>].

⁸³Williams, J. G., M. H. Gessel, B. P. Sandford, and J. J. Vella. 1996. Evaluation of factors affecting juvenile Chinook salmon fish guidance efficiency. Report to U.S. Army Corps of Engineers, Walla Walla District by NOAA, Natl. Mar. Fish. Serv., Seattle, 35 p. [avail. at https://www.nwfsc.noaa.gov/assets/26/6850_03012012_121748_Williams.et.al.1996.pdf].

smaller diameter than those with a larger diameter. Fish may have detected this acceleration in the original 15.2 cm diameter orifices and avoided getting trapped. Since larger orifices have a greater trapping area, fish may not detect the acceleration in time to avoid it. The vertical barrier screen research led to conditions that were somewhat benign in the area of the orifices, while greater velocity and turbulence through the vertical barrier screens existed in areas away from the orifice. We think the effect was to provide "sanctuary" areas near the orifices that attracted fish, and then fish in the area were trapped by the orifice flow.

With the exception of the new Bonneville Dam Second Powerhouse, levels of FGE above 70% were nearly always attainable for steelhead with STS and raised operating gates. However, despite nearly 20 yr of research, a 70% FGE target level was often not attainable throughout the entire migration season at all dams for yearling Chinook salmon, and seldom attained 70% FGE on incidental tests for sockeye salmon.

Of particular concern was the inability under nearly any circumstance to attain 70% FGE for subyearling Chinook salmon. Potentially, these general results were related to fish size. Larger fish with greater swimming abilities may not have responded to the changes in water acceleration to the same extent as did smaller fish. We do note, however, that at dams where measured, subyearling Chinook salmon FGE tended to decrease over the period from early June to August when no changes occurred in guidance systems at dams. The decrease in FGE did correspond to lower vertical distribution of fish passing into turbine intakes.

A number of modifications to the original STS tested at Ice Harbor Dam were made over the next 20 yr and testing led to gains in FGE, however, they were not all straightforward. The 1984 study at Lower Granite Dam indicated that more than STS configurations effected FGE. The interaction of high spill attracting fish toward the spillway in connection with a log

boom designed to reduce debris arriving at the dam, appeared to induce migrants in surface waters to pass through the spillway. This apparently decreased the percentage of guidable fish that entered the turbine intakes in the test unit. Thus, FGE was lower.

Secondly, FGE increased as the season progressed, yet the general test conditions remained unchanged. The changes in FGE appeared related to differences in physiology between fish stocks. Taken together, it suggested that modifications to STS alone would not sufficiently increase FGE to lower the number of fish passing through turbines.

To limit turbine passage might also require major modifications at dams, such as adding trash rack deflectors, redesigning STS, or considering other devices that could intercept a greater percentage of Chinook salmon in the water column flowing into turbine intakes. This was considered a potentially very difficult task to address when looking at the continuing poor measures of FGE after major structural modifications had been made at the new Bonneville Dam Second Powerhouse.

At the time that the initial research on screening systems for turbine intakes began in the 1960's, the dams installed in the lower Snake and Columbia rivers were designed primarily to produce power. They were built as "run of river" structures with little storage capacity. All river discharge was expected to go through turbines unless total discharge exceeded powerhouse capacity. It focused the research to develop systems to divert fish from turbine passage.

Despite completion of bypass systems at nearly all dams, the upriver salmon stocks did not rebound to historic levels. This has led to voluntary spill programs at dams as a further means of decreasing turbine passage. Had this operation scenario been in effect at the time the screening system studies began, it is not clear that all of systems now in place at each dam would have been installed.

During most of the 30 yr of screening research, it was quite clear that

fish behavior played a significant role in whether or not some screening configurations worked. Despite this recognition, the tools needed to determine fine-scale fish behavior and the resolution of hydraulic conditions on the scale at which fish responded was unknown.

In recent years, technology improvements with computers, videography, and modeling has made the ability to obtain this information feasible. Where not known, we highly recommend initially focusing efforts at quantifying fish behavior for species of interest under variable flow conditions, prior to design, construction, and installation of prototype screening systems envisioned to divert or guide fish at dams.

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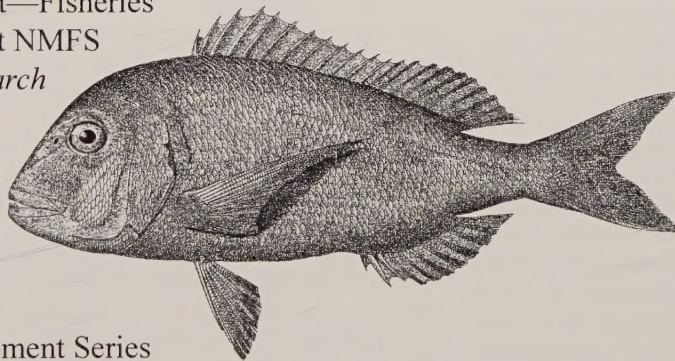
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